Permafrost resilience in the era of climate change and Earth system modeling

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In this analysis from Everest Group, explore the resilience of permafrost in the context of climate change and earth system modeling, with an emphasis on how science and technology are enhancing Arctic stability and global risk management

Seismic signals in the ice: Why permafrost research matters now

Permafrost – perennially frozen ground composed of soil, rock, and organic material – underpins nearly one-quarter of the Northern Hemisphere's land surface. It stabilizes Arctic ecosystems, supports infrastructure, and locks away vast stores of carbon accumulated over millennia. But with global temperatures rising, this frozen foundation is rapidly degrading.

Thaw-induced disruptions extend far beyond local impacts. Crumbling buildings, collapsing roads, and fractured pipelines are now typical across Alaska, Northern Canada, and Russia. Simultaneously, methane and carbon dioxide emissions from thawing permafrost contribute to a warming feedback loop, raising concerns about tipping points in the global climate system (Schuur et al., 2023). These cascading effects demand urgent scientific attention and an international response.

Promoting permafrost research: A global imperative

The complexity of permafrost systems calls for coordinated, interdisciplinary research. Organizations such as the Global Terrestrial Network for Permafrost (GTN-P) and the International Permafrost Association (IPA) are central to developing standardized protocols, harmonizing datasets, and advancing model validation (Obu et al., 2024). However, scientific advancement alone is insufficient.

Effective communication of findings to non-scientific audiences –including policymakers, urban planners, Indigenous leaders, and educators – is equally critical. Community-driven adaptation planning depends on accessible, context-rich data. Furthermore, Indigenous knowledge systems offer land-based observations that complement scientific monitoring, improving model calibration and local resilience strategies (Ford et al., 2021).

Understanding permafrost: Composition, geography, and surface dynamics

Permafrost is classified by coverage extent – continuous, discontinuous, sporadic, or isolated – and varies in composition depending on region and geologic history. It often contains a complex mix of frozen mineral soils, organic matter, and ice lenses. Above this lies the active layer, which thaws each summer and refreezes in winter.

The active layer is pivotal in surface hydrology, soil biogeochemistry, and infrastructure stability. Shifts in thickness are among the earliest indicators of climate- induced degradation. Over the past two decades, this layer has thickened by 0.5 to 1.0 meters in many Arctic sites, leading to altered water flow patterns, increased erosion, and greater vulnerability to thermokarst development (NSIDC, n.d.; ScienceDirect, 2020).

Tracking the thaw: Historical warming and model projections

Since the late 1960s, borehole records and satellite data have documented a consistent warming trend in permafrost zones. Ground temperatures have increased by 0.3°C to over 1°C per decade, with Arctic and sub- Arctic regions showing the most rapid change (EPA, 2023). Mountain permafrost is also warming, though local snow insulation and rock-type variability introduce additional complexity.

Climate models project further degradation throughout the 21st century. Under Representative Concentration Pathway 8.5 (RCP8.5), near-surface permafrost could retreat up to 99% in vulnerable regions by 2100 (Zhao et al., 2022). However, many models lack mechanisms for abrupt thaw events or permafrost-carbon feedbacks, resulting in conservative estimates of physical and atmospheric impacts (Schädel et al., 2024).

Deepening layers, rising emissions: Quantifying the risks

While complete permafrost disappearance is not imminent, the deepening of the active layer is widely projected. In some boreal zones, active-layer thickness may increase by 50–100% by the century’s end, driven by warmer summers and delayed winter refreezing (Xia et al., 2024). This poses serious risks for infrastructure: in Russia’s Yamal Peninsula alone, thaw-related road damage has exceeded US$1.3 billion.

Beneath these structural concerns lies an even larger threat. Permafrost stores over 1,400 gigatons of organic carbon – nearly twice the carbon currently in Earth’s atmosphere. If released, emissions could total 30 to 150 billion metric tons of CO_2 equivalent by 2100, raising global mean temperatures by up to 0.3°C and inflating mitigation costs by as much as US$70 trillion (NOAA, 2023; CPO, 2024). Yet fewer than 10% of models used in IPCC assessments include this feedback, highlighting a significant gap in climate forecasting.

From monitoring to mitigation: Charting a resilient path forward

Meeting the challenge of permafrost thaw requires investment in research infrastructure and decision-making frameworks. Enhanced Earth system models that integrate permafrost-carbon feedbacks and abrupt thaw mechanisms will be essential for accurate

forecasting. Remote sensing tools from ESA's Climate Change Initiative and the NASA ABoVE program are helping to bridge observational gaps.
Equally important is the implementation of science- backed policy. Arctic building codes, transportation design, and land-use planning must account for future permafrost behavior.

Partnerships with Indigenous communities offer valuable insights and governance models grounded in stewardship. As thawing soils reshape Arctic and sub-Arctic environments, scientific foresight must be paired with inclusive, adaptive action.

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