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Contrasting Climate Stressors in Permafrost Regions: Maritime Kamchatka and Continental Yakutia

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Abstract

Climate change in high-latitude regions is often interpreted primarily through rising temperatures and permafrost degradation. However, in permafrost economies, environmental disruption increasingly emerges from how warming alters snow regimes, moisture dynamics, and ground processes rather than from cold extremes alone. This study develops a mechanism-based comparative synthesis of two contrasting permafrost regions in the Russian Far East—continental Yakutia and maritime Kamchatka—to examine why climate change disrupts economic activity in some cold regions while remaining operationally manageable in others.

The analysis shows that climate change operates through distinct pathways across continental and maritime permafrost regimes. In maritime Kamchatka, warming enhances atmospheric moisture and increases the likelihood of concentrated snowfall events that disrupt transportation networks, restrict mobility, and trigger abrupt system-wide interruptions to regional economic activity. In contrast, in highly continental Yakutia, extreme cold represents a historically normalized condition around which socio-economic systems have long been organized. There, climate change manifests primarily through thermokarst development, wildfire activity, and reduced nocturnal cooling in summer, gradually destabilizing infrastructure without immediately halting economic operations.

By integrating winter and summer processes, the study highlights an emerging seasonal asymmetry of climate risk in permafrost regions. Snowfall extremes act as immediate barriers to economic continuity, while extreme cold functions as a chronic but adapted stress. These findings challenge temperature-centric interpretations of Arctic climate risk and underscore the importance of regime-specific adaptation strategies that distinguish between snow-driven disruption and cold-adapted resilience in permafrost economies.

1. Introduction

Climate change is increasingly expressed not only through gradual warming trends but also through disruptive extremes that directly interrupt economic activity, public services, and everyday life, particularly in high-latitude permafrost regions. While much of the literature emphasizes long-term processes such as permafrost thaw and ecosystem transformation, recent evidence suggests that short-term climatic shocks—especially snowfall extremes—can generate immediate socio-economic disruption that rivals or exceeds the impacts of extreme cold itself (Nelson & Anisimov, 1993).

A growing body of research documents systematic changes in cold-region climate regimes, including increased winter precipitation, altered snow accumulation, and heightened variability in freeze–thaw dynamics (da Cunha, et al., 2022). In maritime-influenced permafrost regions, rising atmospheric moisture has amplified snowfall intensity, while continental interiors remain dominated by extreme cold but comparatively lower snow loads. These diverging trends raise a fundamental question that remains insufficiently synthesized: is economic disruption in permafrost regions—manifested through interruptions to transportation systems, infrastructure stability, and the continuity of regional economic

activity—driven primarily by cold extremes or by snow-related hazards that challenge existing adaptation systems?

This question has gained renewed relevance following recent climate-related disruptions in snow-prone regions of the Russian Far East. In Kamchatka, extreme snowfall events have coincided with widespread suspension of transportation, work, and public services, compounding an already dense multi-hazard environment shaped by seismic activity, volcanism, and tsunami exposure (Tronin et al., 2004; Abramov et al., 2008; Pinegina et al., 2026; Gusiakov et al., 2024). Paleoclimate and instrumental records suggest that variations in snow cover have long been a feature of Kamchatka's climate system, reflecting broader shifts in atmospheric circulation and moisture availability (Hammarlund et al., 2015; Brooks et al., 2015)

By contrast, Yakutia (the Sakha Republic) represents one of the coldest inhabited regions on Earth, where winter temperatures routinely fall below − 50°C. Despite ongoing climate change and significant permafrost warming, economic and social activity in Yakutia rarely comes to a complete halt during extreme cold events (Krillina et al., 2023). Instead, adaptation has historically been embedded into infrastructure, land use, and institutional practice, including winter road systems (zimniks), permafrost-specific engineering solutions, and localized coping strategies developed over decades of exposure to severe cold (Boike et al., 2016; Zhang et al., 2023).

Recent studies nevertheless show that Yakutia is undergoing profound transformation under climate change, including accelerated urban warming in Yakutsk (Li et al., 2024), increasing wildfire intensity and spatial extent (Narita et al., 2021; Glückler et al., 2026; Jones et al., 2022), and growing tension between economic development and environmental sustainability (Gavrilyeva et al., 2020; Durova & Ryan, 2024). Governance-related constraints—such as fiscal centralization and limited local policy autonomy—further complicate long-term adaptation, even in regions with strong experiential knowledge of climatic extremes (da Cunha et al., 2022; Yokogawa, 2024).

Taken together, these contrasting trajectories suggest that economic disruption in permafrost regions—particularly interruptions to transportation systems, infrastructure stability, and the continuity of regional economic activity—cannot be explained by climatic severity alone. Instead, disruption depends on how specific climate stressors interact with institutional preparedness, governance structures, and regional hazard environments. The comparison between Kamchatka and Yakutia is analytically useful because both regions are located within the Russian Federation and share exposure to permafrost conditions and ongoing climate change. However, they differ substantially in their climatic regimes, hazard landscapes, governance arrangements, and economic structures.

Kamchatka is characterized by a maritime climate, dense multi-hazard exposure—including earthquakes, volcanic activity, and tsunami risk—and a relatively centralized administrative structure. Yakutia (Sakha Republic), by contrast, is governed as an autonomous republic within Russia, operates under an extremely continental climate, and is primarily exposed to environmental processes such as extreme cold, permafrost thaw, and wildfire dynamics rather than complex geophysical hazards. Population density and economic structures also differ significantly between the two regions.

Climatic evidence further indicates that summer temperatures in Kamchatka declined between the 1940s and the 1970s before entering a warming phase after the 1970s (Sano et al., 2010). Although wildfire activity in Kamchatka is generally more limited than in continental regions such as Yakutia, large wildfire events can still occur. For example, a major fire in 2016 burned approximately 600,000 acres of boreal forest and tundra in eastern Kamchatka (USGS, 2016).

In contrast, wildfire activity constitutes a more significant environmental stressor in Yakutia. The region has experienced several extreme fire seasons in recent years; in 2021 alone, nearly 8.5 million hectares of forest burned across the Republic of Sakha (Yakutia), making it one of the largest wildfire events recorded in Russia (Desyatkin et al., 2024; Tomshin & Solovyev, 2022).

These contrasts allow the analysis to move beyond simple climatic comparisons and instead examine how different combinations of climate regimes, hazard environments, and governance capacities shape economic outcomes under climate change. In regions such as Kamchatka, where intense snowfall intersects with complex hazard landscapes and limited institutional memory for snow-driven crises, climate change tends to manifest as abrupt disruptions to transportation, infrastructure reliability, and the continuity of economic activity. In highly continental regions such as Yakutia, extreme cold constitutes a historically normalized condition around which socio-economic systems have long been organized, resulting in continuity rather than collapse—at least in the short term.

1. Climate Stressors in Permafrost Regions: Contrasting Hazard Regimes and Institutional Exposure

Permafrost regions are experiencing rapid climatic change, yet the socio-economic consequences of these changes differ sharply across regions, even where biophysical conditions appear comparable. While climate change research has traditionally emphasized gradual warming trends and permafrost degradation, growing evidence suggests that the dominant type of climate stressor—snow versus cold—plays a decisive role in shaping disruptions to transportation systems, infrastructure stability, and the continuity of regional economic activity, particularly when interacting with institutional preparedness and governance capacity.

Two regions in the Russian Far East—Kamchatka and Yakutia (the Sakha Republic)—provide a compelling contrast. Both are high-latitude territories characterized by permafrost conditions and increasing climate variability. However, they differ fundamentally in their climate regimes, hazard constellations, and modes of socio-economic adaptation, leading to markedly different responses to climate-related stress.

1.1 Kamchatka: Maritime Climate, Multi-Hazard Exposure, and Acute Disruption

Kamchatka is shaped by a maritime-influenced cold climate, where relatively moderate winter temperatures coexist with high atmospheric moisture. This climatic configuration enhances winter precipitation and favors intense snowfall events, particularly during cyclonic intrusions. Evidence from paleoclimatic and lacustrine records suggests that snow accumulation and winter moisture variability in Kamchatka are closely linked to long-term atmospheric circulation dynamics rather than representing purely recent anomalies (Hammarlund et al., 2015; Brooks et al., 2015; Self et al., 2015).

Snowfall extremes in Kamchatka occur within an exceptionally dense multi-hazard environment. The peninsula is among the most seismically and volcanically active regions in the world, with frequent strong earthquakes, tsunamis, and persistent volcanic activity interacting with permafrost landscapes (Suprunenko, 1977; Abramov et al., 2008). Recent work documents how major seismic events trigger cascading impacts, including tsunamis with substantial run-up heights and inland penetration that threaten coastal infrastructure and economic activity (Pinegina et al., 2026; Gusiakov et al., 2024). Hydrothermal and geochemical anomalies linked to seismic processes further illustrate the tight coupling between the lithosphere, hydrosphere, and atmosphere in the region (Tronin et al., 2004).

In addition to natural hazards, Kamchatka faces environmental and industrial risks that compound climate-related stress. Studies have identified a dramatic increase in oil-product pollution in the Kamchatka River basin linked to exploratory drilling and abandoned wells, posing long-term risks to fisheries and regional livelihoods (Blokov & Vasil'eva, 2023). Historical marine dumping of radioactive waste southeast of Kamchatka adds another layer of latent environmental vulnerability, with potential downstream effects on productive coastal ecosystems (Morehead et al., 1997).

Taken together, these overlapping hazards create conditions under which extreme snowfall acts as a shock multiplier, rapidly disrupting transportation, public services, and economic activity. Evidence from Kamchatka suggests that such disruptions tend to be acute and episodic, with climate-related events treated as exceptional crises rather than as conditions requiring continuous operational adaptation. This mode of exposure increases the likelihood that snowfall extremes—rather than cold itself—trigger abrupt socio-economic shutdowns.

1.2 Yakutia: Continental Cold, Chronic Extremes, and Institutionalized Adaptation

Yakutia represents a contrasting permafrost environment governed by an extremely continental climate, characterized by prolonged periods of severe cold and comparatively lower snowfall. Winter temperatures frequently fall below − 50°C, making Yakutia one of the coldest inhabited regions globally. Long-standing research has shown that anthropogenic climate change is disproportionately amplified at these high latitudes, leading to rising ground temperatures and progressive shifts in permafrost zonation (Nelson & Anisimov, 1993; Fedorov & Konstantinov, 2009).

Remote sensing and field-based studies reveal substantial landscape transformation across central Yakutia, including changes in lake dynamics, surface wetting and drying, and increasing wildfire activity

(Boike et al., 2016; Glückler et al., 2026). Rapid urban expansion in Yakutsk has intensified land surface warming, further increasing the vulnerability of permafrost beneath critical infrastructure (Li et al., 2024). Engineering-focused studies demonstrate that large industrial facilities in Yakutsk remain operational by explicitly integrating permafrost dynamics into design and management strategies, combining permafrost preservation with controlled thaw where necessary (Zhang et al., 2023).

Despite these profound environmental changes, economic and social life in Yakutia rarely comes to a complete halt during extreme cold events. Adaptation to cold has been institutionalized through infrastructure and practice, most notably through the use of winter roads (zimniks) that enable mobility and supply chains during frozen periods (Kirillina et al., 2023). Indigenous knowledge systems further contribute to adaptive capacity, particularly in managing fire and flood risks under changing climatic conditions (Solovyeva et al., 2020).

However, Yakutia's apparent resilience masks growing structural constraints. Economic growth in the region remains closely tied to greenhouse gas emissions and resource extraction, with limited evidence of decoupling or transition toward low-carbon efficiency (Gavrilyeva et al., 2020; Gavril'eva et al., 2022). Governance studies highlight persistent challenges related to fiscal centralization, limited regional autonomy, and difficult trade-offs between economic development and long-term sustainability (da Cunha et al., 2022; Durova & Ryan, 2024; Yokogawa, 2024). Climate change thus manifests in Yakutia primarily as a chronic stressor, gradually eroding infrastructure reliability and social cohesion rather than producing sudden economic collapse.

1.3 Snow Versus Cold: Reframing Climate Risk Through Economic Continuity

The contrasting experiences of Kamchatka and Yakutia suggest that economic disruption in permafrost regions—particularly interruptions to transportation systems, infrastructure reliability, and the continuity of economic activity—is not determined solely by climatic severity, but by how specific climate stressors interact with historical norms, hazard combinations, and institutional capacity. In maritime regions such as Kamchatka, thermal anomalies and changing precipitation regimes have been associated with increasingly intense snowfall events (Tronin et al., 2024). These snowfall extremes interact with multiple co-occurring hazards, amplifying the likelihood of abrupt disruptions to regional systems. In highly continental regions such as Yakutia, by contrast, extreme cold constitutes a historically normalized condition around which socio-economic systems have long been organized, resulting in continuity rather than immediate disruption (Li et al., 2024). At the same time, rising ground temperatures associated with global warming are destabilizing permafrost foundations across both regions, creating longer-term infrastructure risks that unfold more gradually than the abrupt disruptions associated with snowfall extremes (Sejourne et al., 2015; Kazakov, 2010).

This comparison reframes climate risk in permafrost regions from a purely physical phenomenon into a broader socio-economic and governance challenge. While snowfall extremes can produce abrupt disruptions and extreme cold may be absorbed through long-standing adaptation practices, rising

ground temperatures associated with global warming introduce additional long-term risks through the destabilization of permafrost foundations. Consequently, whether climate hazards translate into economic disruption depends not only on climate dynamics, but also on the extent to which these hazards are anticipated, embedded in institutional practice, and supported by adaptive governance structures. This perspective provides the foundation for the following sections, which examine how crisis management, policy capacity, and institutional memory shape economic outcomes under climate change.

2. Methodology

This study adopts a comparative synthesis-based review to examine how climate change produces different forms of economic disruption across permafrost regions with contrasting climatic regimes, particularly through disruptions to transportation systems, infrastructure stability, and the continuity of regional economic activity. Rather than estimating statistical causal effects, the analysis focuses on identifying mechanisms through which climate stressors interact with institutional and environmental conditions to shape socio-economic outcomes.

Study selection process

The analysis is based on a targeted review of 35 peer-reviewed studies drawn from climatology, permafrost science, hazard research, and socio-economic literature. Relevant publications were identified through searches in Web of Science, Scopus, and Google Scholar using combinations of keywords including permafrost climate change, snowfall extremes, Yakutia, Sakha Republic, Kamchatka climate hazards, Arctic infrastructure vulnerability, thermokarst dynamics, and permafrost urban infrastructure. The literature search was conducted between January 2026 and February 2026. The study selection process and the steps through which the final set of 35 studies was obtained are illustrated in the PRISMA flowchart (Fig. 1), provided in the Appendix.

The study selection process was prepared in accordance with the PRISMA guidelines for systematic reviews (Page et al., 2021). Studies were included if they (1) examined climate-related environmental processes in high-latitude or permafrost regions, (2) provided empirical or analytical insights into environmental hazards, infrastructure vulnerability, or socio-economic impacts, and (3) focused on regions comparable to or directly related to Yakutia or Kamchatka. Studies focusing solely on cryospheric processes without clear implications for infrastructure stability, environmental risk, or economic activity were excluded.

The methodological quality of the selected studies was evaluated using the quality appraisal framework proposed by Zangaro and Soeken (2007). This framework, which is compatible with PRISMA-based systematic review procedures and can be applied across different research fields, assesses methodological rigor using nine evaluation criteria. Each study was scored on a scale from 1 to 9; scores of 7–9 were classified as high quality, 4–6 as moderate quality, and 1–3 as low quality. Studies assessed

as low quality were excluded from the analysis to ensure that the synthesis relied on methodologically reliable evidence.

The collected studies were systematically grouped according to their geographical focus in order to enable a comparative synthesis of climate impacts in the Russian Far East. In particular, the reviewed literature was organized around two regional clusters: Yakutia (Sakha Republic) and Kamchatka. These regions were selected because they represent contrasting climate regimes within permafrost environments while sharing comparable high-latitude conditions and exposure to ongoing climate change.

The analytical strategy therefore follows a comparative synthesis-based review, in which findings from the selected studies are integrated and interpreted within each regional cluster and then compared across the two regions. Grouping the literature in this way allows the analysis to identify how different climate regimes—continental cold in Yakutia and maritime snowfall dynamics in Kamchatka—translate into distinct environmental risks and pathways of economic disruption.

Analytical approach

The analysis proceeds through a mechanism-oriented synthesis of the selected literature. Evidence from climatology, permafrost dynamics, hazard research, and governance studies is integrated to identify how specific climate stressors interact with regional environmental conditions and institutional structures.

Rather than testing statistical hypotheses, the study traces causal pathways linking climatic processes (e.g., snowfall intensity, wildfire dynamics, thermokarst development) to infrastructural and economic outcomes such as transportation disruption, infrastructure instability, and operational continuity.

The comparative synthesis enables the identification of two distinct climate disruption pathways:

1. Snow-driven disruption, where intense snowfall events directly interrupt mobility and economic activity (Kamchatka).
2. Cold-adapted continuity, where extreme temperatures are historically normalized and disruption emerges primarily through gradual environmental degradation processes (Yakutia).

By integrating evidence across disciplines, the method allows the study to highlight how climate risk in permafrost regions is mediated by climatic regimes, hazard interactions, and institutional adaptation rather than by temperature change alone.

3. Comparison Between Kamchatka and Yakutia: Shared Permafrost Conditions but Diverging Climate Disruption Pathways

3.1 Kamchatka: Snowfall Extremes, Multi-Hazard Exposure, and Acute Economic Disruption

Kamchatka represents a permafrost region where climate change manifests primarily through episodic but high-impact disruptions, rather than through continuous operational strain. Although the peninsula is widely recognized for its exposure to seismic and volcanic hazards (Abramov et al., 2008), recent snowfall extremes highlight a distinct vulnerability: snow-related events repeatedly trigger widespread interruptions to transportation, work, and public services, despite winter temperatures that are considerably milder than those observed in continental permafrost regions. This pattern suggests that economic disruption in Kamchatka is shaped not by climatic severity alone, but by the interaction between snowfall intensity, hazard complexity, and the mode of crisis response.

Although total annual precipitation in Kamchatka has not consistently increased—and in some areas has even declined— (Kuksina, 2019; Dolezal et al., 2014) recent climatic shifts have altered the temporal distribution and intensity of precipitation events. Rather than producing steady seasonal accumulation, precipitation increasingly occurs in concentrated episodes, often delivering large amounts of snowfall over short periods. Such shifts in precipitation regimes can generate operational disruptions even without an overall increase in annual precipitation totals.

3.1.1 Snowfall as a High-Impact Stressor in a Maritime Permafrost Climate

Kamchatka's maritime-influenced climate is characterized by elevated atmospheric moisture and frequent cyclonic activity, conditions that favor intense snowfall accumulation during winter months. Long-term palaeoclimatic evidence demonstrates that increasing snow cover and wetter winters have been persistent features of Kamchatka's climate variability, reflecting large-scale atmospheric circulation dynamics rather than isolated recent anomalies (Hammarlund et al., 2015; Brooks et al., 2015).

Under contemporary climate change, these background conditions translate into recurrent high-impact snowfall events that rapidly exceed the capacity of transportation and logistical systems. In contrast to regions where cold dominates as the primary stressor, snowfall in Kamchatka directly impedes mobility, access to services, and supply chains. As a result, snow functions not merely as a climatic variable but as a critical operational constraint with immediate economic consequences.

3.1.2 Compound Hazard Context and Cascading Disruption

Snowfall-related disruption in Kamchatka is amplified by the region's exceptionally dense multi-hazard context. The peninsula is among the most seismically active areas globally, with major earthquakes capable of generating destructive tsunamis that threaten coastal settlements and economic infrastructure (Pinegina et al., 2026; Gusiakov et al., 2024). Volcanic activity further complicates risk

management, as permafrost on active volcanic systems introduces unstable ground conditions that can be rapidly altered by thermal or seismic forcing (Abramov et al., 2008; Suprunenko, 1977).

Hydrothermal and geochemical anomalies associated with seismic processes illustrate the tight coupling between lithospheric dynamics and atmospheric or hydrological responses in the region (Tronin et al., 2004). Within this setting, snowfall acts as a compounding stressor, increasing the likelihood that otherwise manageable hazards escalate into cascading disruptions. Transport interruptions caused by heavy snow accumulation become particularly consequential where alternative routes are limited by mountainous terrain, coastal geography, or prior hazard impacts.

3.1.3 Environmental Background Risks and Economic Sensitivity

In addition to natural hazards, Kamchatka faces persistent environmental and industrial pressures that heighten regional sensitivity to climate-related disruption. A sharp increase in oil-product pollution in the Kamchatka River basin since the early 2000s has been linked to exploratory drilling and inadequately sealed wells, posing risks to fisheries and regional livelihoods (Blokov & Vasil'eva, 2023). Historical marine dumping of radioactive waste in the North Pacific southeast of Kamchatka represents a further latent environmental risk, with potential long-term implications for coastal ecosystems depending on ocean circulation pathways (Morehead et al., 1997).

At the same time, long-term climatic indicators suggest that the general structure of weather conditions in Kamchatka has remained relatively stable in terms of mean values (Pogorelov, 2025). However, recent observations indicate that the disruptive impacts of climate variability are increasingly associated with changes in the temporal distribution and intensity of precipitation rather than with gradual shifts in average climatic conditions. In particular, concentrated snowfall events occurring over short periods can rapidly disrupt transportation systems, access to services, and emergency response capacity.

Under these circumstances, background environmental pressures further constrain the margin for operational flexibility during extreme events. When heavy snowfall interrupts transport or emergency response systems, economic activity is more readily disrupted, as regional infrastructures and livelihoods already operate under multiple environmental constraints.

3.1.4 Acute Disruption Versus Routinized Stress

A defining feature of Kamchatka's response to snowfall extremes is that disruption tends to be acute and event-driven. Snow-related hazards are experienced as short-term shocks that prompt temporary suspension of work, education, and transportation, rather than as chronic conditions around which economic systems are organized. This contrasts with regions where persistent exposure to extreme cold has historically driven the routinization of adaptation measures.

In Kamchatka, the combination of maritime snowfall dynamics and multi-hazard exposure means that snowfall extremes rapidly translate into system-wide interruptions, even in the absence of record-

breaking cold. Economic disruption thus reflects the operational impact of snow as a mobility- and access-limiting stressor, rather than the physiological or material limits imposed by low temperature alone.

3.1.5 Implications for Climate Risk Assessment

The Kamchatka case demonstrates that in permafrost regions snowfall can, under certain conditions, pose a more immediate threat to economic continuity than extreme cold. This is particularly evident where snowfall interacts with complex hazard landscapes and sensitive logistical systems. In such contexts, disruption is driven not only by climatic severity but also by the relative novelty of the hazard and the limited institutional readiness to manage it. In Kamchatka, heavy snowfall events have historically been less central to regional risk management, making large snow accumulations operationally difficult to manage. Importantly, recent climatic changes do not necessarily imply an increase in total precipitation (Kuksina, 2019; Dolezal et al., 2014. Instead, evidence suggests that the temporal distribution and intensity of precipitation events are shifting, producing more concentrated snowfall episodes. These short-duration but intense events can rapidly disrupt transportation systems, access to services, and regional mobility, shifting the dominant mode of risk from gradual environmental degradation toward episodic but severe disruption.

This finding suggests the importance of distinguishing between acute, snow-driven interruptions and chronic, cold-related stress when assessing climate risk and adaptation strategies in high-latitude regions. Kamchatka illustrates how regions with relatively moderate winter temperatures may nonetheless experience disproportionate economic disruption when precipitation regimes produce concentrated snowfall events that interrupt transportation systems, infrastructure reliability, and the continuity of economic activity.

3.2 Yakutia: Continental Cold, Permafrost Transformation, and Chronic Environmental Stress

3.2.1 Extreme Cold as a Historically Normalized Condition

Yakutia represents one of the most extreme continental climate environments in the world, where winter temperatures frequently fall below − 50°C (Zhang et al., 2023). Despite this severity, extreme cold has historically functioned as a normalized environmental condition rather than an episodic crisis. Over time, infrastructure, mobility systems, and everyday economic activities have been adapted to persistent low temperatures. Seasonal winter roads (zimniks), cold-resistant construction techniques, and operational routines designed for prolonged cold exposure allow transport, supply chains, and public services to continue even under severe winter conditions (Kuklina et al., 2022). As a result, extreme cold rarely produces immediate system-wide interruptions comparable to those observed in snowfall-dominated regions.

3.2.2 Permafrost Thaw and Thermokarst Processes

Under contemporary climate change, the dominant environmental transformation in Yakutia is not increased snowfall but the gradual destabilization of permafrost landscapes. Rising ground temperatures and longer warm seasons accelerate thermokarst development, producing ground subsidence, expanding thaw lakes, and localized infrastructure instability (Sejourne et al., 2015). These processes unfold gradually and spatially unevenly, affecting roads, pipelines, and urban foundations over extended time horizons rather than triggering immediate regional shutdowns (Kuklina et al., 2022). Consequently, climate change in Yakutia primarily manifests through progressive environmental transformation rather than through abrupt climatic shocks.

3.2.3 Wildfire Intensification and Landscape Change

Climate warming in Yakutia has also contributed to increasing wildfire intensity across boreal forest landscapes (Glckler et al., 2024). Higher summer temperatures, prolonged dry periods, and changing vegetation conditions have increased the vulnerability of large forest areas to fire (Glückler et al., 2026). Wildfires can damage infrastructure, disrupt transportation routes, and degrade air quality, yet their impacts typically unfold over broader spatial and temporal scales (Boike et al., 2016). Unlike snowfall-induced disruptions that halt mobility almost immediately, wildfire impacts tend to accumulate gradually through environmental degradation and landscape transformation.

3.2.4 Infrastructure Stability and Urban Permafrost Challenges

Urban areas in Yakutia, particularly Yakutsk, face growing challenges associated with permafrost thaw and urban warming (Mege, 2015; Boike et al., 2016). Infrastructure built on permafrost foundations relies on thermal stability to maintain structural integrity (Kuklina et al., 2022). As warming reduces the effectiveness of natural cooling processes, including nocturnal temperature drops during summer, ground temperatures rise and the active layer thickens. These changes increase the risk of long-term infrastructure instability in buildings, roads, and energy systems (Sejourne et al., 2015). However, these impacts typically emerge as chronic engineering and maintenance challenges rather than sudden disruptions to economic activity.

3.2.5 Chronic Environmental Stress Rather Than Acute Disruption

Taken together, these processes illustrate a pattern of chronic environmental stress rather than acute climatic disruption. In Yakutia, extreme cold has historically been incorporated into socio-economic systems through long-term adaptation practices. Climate change therefore tends to destabilize infrastructure and ecosystems gradually, rather than producing sudden interruptions to transportation and economic activity (Solovyeva et al. 2020). This contrasts sharply with maritime permafrost regions such as Kamchatka, where intensified snowfall events can rapidly translate into system-wide disruptions. The Yakutia case thus highlights how historically normalized climatic conditions can sustain operational continuity even as long-term environmental stresses intensify.

3.3. Contrasting Climate Impacts and Governance Structures in Yakutia and Kamchatka

Although Yakutia and Kamchatka are both located in high-latitude environments within the Russian Far East, their climatic regimes differ substantially due to contrasting continental and maritime influences. Yakutia is characterized by an extremely continental climate with very low winter temperatures and large seasonal temperature amplitudes, whereas Kamchatka experiences a maritime-influenced cold climate with comparatively milder winters and higher atmospheric moisture. These climatic contrasts shape the dominant environmental risks faced by each region and influence how climate stressors translate into economic and infrastructural disruption. As shown in Table 1, winter temperatures in Yakutia are substantially lower than in Kamchatka, while summer temperatures remain relatively moderate in both regions despite their differing climatic regimes. This contrast provides an important contextual basis for understanding why climate change manifests through different environmental processes and risk pathways in the two regions.

Table 1
Average winter and summer temperatures in Yakutia (Yakutsk) and Kamchatka (Petropavlovsk-Kamchatsky)

Region	Winter avg (Jan)	Summer avg (Jul/Aug)	Climate type
Yakutia (Yakutsk)	~ −36°C	~ 19–20°C	extreme continental
Kamchatka (Petropavlovsk-K.)	~ −10°C	~ 13–14°C	maritime

Sources

Copernicus Climate Change Service (C3S, 2023), *ERA5 reanalysis dataset*; NOAA National Centers for Environmental Information (NCEI, 2024), *Climate Data Online*; Climate-Data.org (2024), *Climate database for Yakutsk and Petropavlovsk-Kamchatsky*.

3.3.1 Divergent Climate Change Pathways in Permafrost Regions

Although Yakutia and Kamchatka are both located within high-latitude permafrost zones, climate change manifests through fundamentally different physical processes in each region, producing distinct risk profiles and socio-economic consequences.

In Yakutia, climate change has become an important driver of environmental change, contributing to extreme fire seasons, permafrost thaw, and thermokarst development (Solovyeva et al., 2021). Rising summer temperatures, prolonged dry periods, and increasing vegetation flammability have contributed to larger burned areas and more severe fire seasons, even where fire frequency has not increased proportionally. These processes interact with continuous permafrost, accelerating ground subsidence, lake expansion, and infrastructure vulnerability through thermokarst formation.

By contrast, Kamchatka has experienced climate change predominantly through increasing snowfall intensity and winter precipitation, driven by its maritime exposure to moist Pacific air masses. While permafrost exists in Kamchatka, it is spatially discontinuous and largely confined to mountainous or elevated zones. As a result, permafrost degradation plays a secondary role compared to snow-driven disruption, which directly affects transportation, access to services, and economic activity.

This divergence underscores a key point: climate change does not impose a uniform stressor across permafrost regions, but instead amplifies the dominant vulnerabilities associated with each region's climatic regime.

3.3.2 Climatic Regimes: Continental Dry Cold versus Maritime Snow-Dominated Winters

Yakutia is governed by an extremely continental climate, characterized by very low winter temperatures and minimal atmospheric moisture. During winter, the region is dominated by the Siberian High, a persistent high-pressure system that suppresses cloud formation and precipitation. As a result, winters are exceptionally cold but relatively dry; snowfall tends to be light, powdery, and limited in accumulation.

Kamchatka, in contrast, is shaped by a maritime climate regime, strongly influenced by the Pacific Ocean. Moist air masses interacting with cold conditions produce intense snowfall events, sometimes delivering in a single storm more snow than Yakutia receives over an entire winter. These snow-dominated extremes are operationally disruptive even when temperatures remain well above the physiological or technical thresholds commonly associated with extreme cold.

Thus, while Yakutia experiences chronic thermal stress, Kamchatka is exposed to episodic but high-impact snow shocks. This distinction is central to understanding why economic disruption unfolds differently across the two regions, with snow-driven events producing abrupt interruptions to mobility and services in Kamchatka, while extreme cold in Yakutia is largely absorbed within systems adapted to persistent low temperatures.

3.3.3 Governance Structures and Policy Capacity

The contrasting climate impacts observed in Yakutia and Kamchatka are also mediated by fundamentally different governance arrangements that shape regional capacity to manage environmental risks. Yakutia (the Sakha Republic) holds the status of an autonomous republic within the Russian Federation. It possesses its own constitution, a clearly articulated ethnic identity, and formal recognition of the Sakha language in education and public life. Legislative authority is exercised through a regional parliament, and executive power is vested in a locally elected head of the republic. This institutional structure provides Yakutia with greater policy discretion, particularly in budgeting, regional planning, and crisis response—factors that influence how climatic and environmental stresses are absorbed by regional systems.

Yakutia's substantial natural resource base—most notably diamonds and gold—further enhances its fiscal bargaining power with the federal center. Revenues generated by large extractive enterprises allow regional authorities to maintain infrastructure and sustain region-specific policy priorities, which can support the continuity of economic activity even under severe environmental conditions.

Kamchatka, by contrast, is organized as a federal territory (krai) governed under a charter rather than a constitution. Executive authority is exercised by a governor operating within a more centralized administrative framework, with comparatively limited legislative autonomy. The region's economic structure also differs substantially: Kamchatka relies heavily on fisheries, tourism, and federal transfers, lacking the scale of extractive revenue that underpins Yakutia's fiscal capacity. As a result, Kamchatka exhibits greater dependence on federal support and more limited regional discretion in long-term planning and crisis management.

These institutional differences shape how climate-related hazards translate into economic outcomes. In regions with greater fiscal autonomy and established adaptation practices, such as Yakutia, extreme environmental conditions tend to be absorbed within existing governance and infrastructure systems. In more centralized and hazard-exposed regions such as Kamchatka, climatic shocks—particularly intense snowfall—are more likely to produce abrupt disruptions to economic activity.

3.3.4 Crisis Management Logics and Operational Response

Differences in governance and hazard exposure produce distinct crisis management patterns in the two regions. In Yakutia, long-term exposure to extreme cold and environmental hazards has created operational routines designed to maintain energy supply, transportation, and basic services even under severe conditions, allowing economic activity to continue during climatic stress (Ksenofontov & Petrov, 2024; Yokogawa, 2024). In Kamchatka, however, crisis management is shaped by the region's exposure to earthquakes, volcanic activity, and tsunamis, and by a more centralized administrative framework in which risk management policies are largely coordinated through federal emergency institutions rather than region-specific strategies (D'iakov, 2016). Consequently, heavy snowfall events in Kamchatka are more likely to trigger temporary suspension of transport, work, and public services, whereas comparable environmental stress in Yakutia is more often absorbed within established operational routines.

3.3.5 The Loss of Nocturnal Cooling in Continental Cities: Urban Warming and Foundation Instability in Yakutsk

Recent climatic changes indicate that the traditional cooling advantage of continental climates is weakening, particularly in urban environments such as Yakutsk. Historically, extreme diurnal temperature ranges—marked by strong nighttime cooling—acted as a stabilizing mechanism for permafrost foundations. Clear skies, dry air, and long radiative cooling periods allowed accumulated daytime heat to dissipate efficiently, preserving frozen ground conditions beneath infrastructure.

However, observations from Yakutsk increasingly point to the emergence of "bright nights"—periods during summer when nocturnal cooling is substantially reduced due to elevated air temperatures,

increased cloudiness, and urban heat retention. Under these conditions, nighttime temperatures remain sufficiently high to prevent ground re-freezing, eliminating the thermal recovery phase that previously protected permafrost foundations.

This shift has profound implications for urban stability. Without effective nocturnal cooling, heat accumulates within the active layer, accelerating permafrost warming beneath buildings, roads, and energy infrastructure. As a result, even in a city defined by extreme winter cold, summer thermal stress becomes the dominant driver of foundation instability. Yakutsk remains one of the coldest cities on Earth, yet its permafrost foundations are increasingly threatened not by winter severity, but by persistent summer warmth and the loss of diurnal thermal contrast. In this context, climate change undermines the very climatic feature—continental cooling—that historically enabled human settlement and economic continuity in Yakutia.

3.3.6 Summer Thaw, Soil Saturation, and Seismic Amplification in Kamchatka

In Kamchatka, climate change introduces a different but equally destabilizing summer mechanism. While winter disruption is dominated by snowfall, summer thaw fundamentally alters ground mechanical properties, transforming frozen or semi-frozen soils into water-saturated, low-strength substrates.

As accumulated winter snow melts, surface and subsurface layers become increasingly waterlogged, producing widespread mud and slurry conditions. Unlike regions with continuous permafrost reinforced by deep pile foundations, much of Kamchatka's built environment is not anchored to bedrock through extensive concrete piling, reflecting historical construction practices adapted primarily to seismic, rather than permafrost, risk.

Under these conditions, soil softening during summer significantly amplifies seismic vulnerability. Water-saturated sediments are prone to deformation and loss of bearing capacity, increasing the risk of ground failure during even moderate seismic events. In effect, climate-driven thaw transforms earthquakes from episodic hazards into seasonally amplified threats, where identical seismic forces produce far greater damage during summer than in winter.

This interaction illustrates a critical but underexplored climate–hazard coupling: Warming does not reduce seismic risk in Kamchatka—it intensifies it indirectly by weakening the ground itself. Climate change thus reshapes not only the frequency of disruption, but the mechanical response of the landscape to non-climatic hazards.

4. Discussion

Taken together, these dynamics indicate that climate change in permafrost regions increasingly operates across multiple seasons rather than through winter extremes alone. In Yakutia, summer warming and the loss of nocturnal cooling progressively destabilize permafrost foundations despite the persistence of

extreme winter cold. In Kamchatka, seasonal thaw and soil saturation reduce ground stability and amplify seismic and infrastructural vulnerability in a region already exposed to earthquakes and volcanic activity.

These processes suggest that while winter conditions remain sharply differentiated between continental and maritime regimes, summer warming introduces a partially shared source of risk. Climate change therefore weakens the traditional seasonal separation between operational stability and environmental hazard, extending vulnerability beyond winter disruptions.

This seasonal asymmetry reinforces the central argument of the study: climate risk in permafrost regions cannot be explained by temperature or cold extremes alone. Instead, the interaction between snowfall dynamics, moisture regimes, permafrost stability, and regional hazard environments determines whether climate stress produces abrupt interruptions to economic activity or gradual infrastructural destabilization..

4.1. Limitations

This study develops a synthesis-based analysis drawing on published literature across climatology, permafrost science, hazard research, and socio-environmental studies. Rather than introducing new primary observational or econometric data, the contribution lies in a mechanism-based comparison that integrates findings from different disciplines to explain how climate stressors translate into distinct forms of disruption across permafrost regions.

Several limitations should be acknowledged. First, the analysis focuses on two emblematic regions—Yakutia and Kamchatka—which limits direct generalization to all permafrost environments. However, these cases were selected because they represent contrasting end-members of continental dry-cold and maritime snow-dominated climate regimes. Second, economic disruption is examined primarily through documented interruptions to transportation, infrastructure stability, and operational continuity rather than through standardized economic loss metrics, which remain unevenly reported across Arctic regions. Finally, while governance and institutional capacity are discussed as contextual mediators of climate impacts, the study does not attempt a formal institutional performance assessment.

These limitations reflect the scope of a climate-mechanism-focused synthesis but also highlight directions for future research. Comparative empirical studies combining climate observations, infrastructure performance data, and regional governance analysis would provide a valuable next step in quantifying the pathways through which climate change affects economic systems in permafrost regions.

5. Conclusion

This study shows that climate change affects permafrost-region economies through distinct physical pathways rather than through climatic severity alone. In maritime permafrost regions such as

Kamchatka, warming enhances atmospheric moisture and concentrated snowfall events that can disrupt transportation networks, restrict mobility, and interrupt the functioning of regional infrastructure even under relatively moderate winter temperatures. In highly continental regions such as Yakutia, by contrast, extreme cold remains operationally manageable, while warming manifests through thermokarst development, wildfire activity, and the loss of nocturnal cooling, gradually destabilizing buildings, roads, and energy systems.

By integrating winter and summer processes, the analysis demonstrates that climate risk in permafrost regions is increasingly seasonally asymmetric. Snow and cold operate as fundamentally different stressors: snowfall can immediately block mobility and connectivity, whereas extreme cold represents a chronic environmental condition around which socio-economic systems have historically adapted. Climate change intensifies both dynamics but through different environmental mechanisms.

These findings suggest that climate adaptation in cold regions cannot rely solely on temperature-based risk assessments. Effective strategies must also account for snowfall regimes, moisture dynamics, and ground stability processes that determine how environmental stress translates into interruptions to transportation, infrastructure reliability, and the continuity of economic activity.

5.1. Implications

The findings have several implications for climate adaptation in high-latitude regions. First, adaptation strategies in permafrost environments should not rely solely on temperature-based risk assessments. In maritime permafrost regions, where warming increases atmospheric moisture and snowfall variability, policy responses should prioritize transportation resilience, snow management, and the continuity of mobility systems during extreme winter events. In highly continental regions such as Yakutia, adaptation priorities are likely to differ, focusing instead on infrastructure stability, permafrost monitoring, wildfire risk management, and the long-term impacts of summer warming on ground mechanics. Recognizing these regime-specific pathways of climate impact can help policymakers anticipate whether climate stress will lead to abrupt disruptions to mobility and infrastructure or to gradual degradation of built environments.

Declarations

Author Declarations

Funding

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Conflicts of Interest / Competing Interests

The authors declare that they have no competing interests.

Ethics Approval

This study does not involve human participants or animals. Therefore, ethical approval was not required.

Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code Availability

Not applicable.

Author Contributions

AHO conceptualized the study, developed the theoretical framework, conducted the analysis, and wrote the manuscript. All authors reviewed and approved the final version of the manuscript.

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Figures

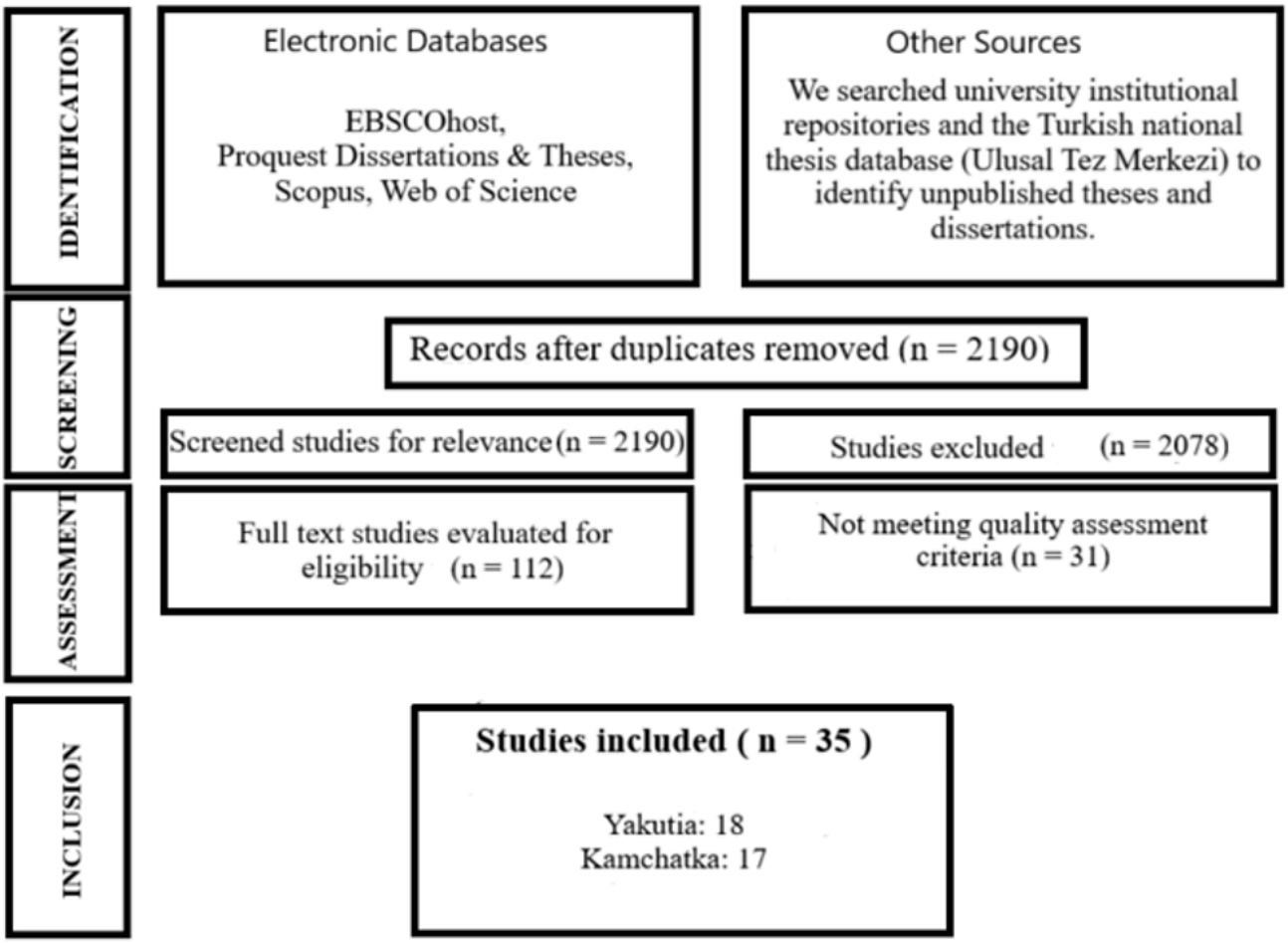


Figure 1

PRISMA Flowchart