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Threshold driven response of permafrost in Northern Eurasia to climate and environmental change: from conceptual model to quantitative assessment

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Numerous efforts have been made to access the environmental impacts of changing climate in permafrost regions using mathematical models. Despite the significant improvements in representation of individual sub-systems, such as permafrost, vegetation, snow and hydrology, even the most comprehensive models do not replicate the coupled non-linear interactions between them that lead to threshold-driven changes. Observations indicate that ecosystems may change dramatically, rapidly, and often irreversibly, reaching fundamentally different state once they pass a critical threshold. The key to understanding permafrost threshold phenomena is interaction with other environmental factors that are very likely to change in response to climate warming. One of such factors is vegetation.

Vegetation control over the thermal state of underlying ground is two-fold. Firstly, canopies have different albedo that affects the radiation balance at the soil surface. Secondly, depending on biome composition vegetation canopy may have different thermal conductivity that governs the heat fluxes between soil and atmosphere. There are clear indications based on ground observations and remote sensing that vegetation has already been changed in response to climatic warming, in consensus with the results of manipulations at experimental plots that involve artificial warming and CO2 fertilization. Under sustained warming lower vegetation (mosses, lichens) is gradually replaced by shrubs. Mosses have high thermal insolating effect in summer, which is why their retreat enhances permafrost warming. Taller shrubs accumulate snow that further warms permafrost in winter. Permafrost remains unchanged as long as responding vegetation intercepts and mitigates the climate change signal. Beyond certain threshold enhanced abundance and growth of taller vegetation leads to abrupt permafrost changes.

Changes in hydrology, i.e. soil wetting or drying, may have similar effect on permafrost. Wetting increases soil thermal conductivity and leads to enhanced active-layer thickness, soil depression, and ponding. Above certain threshold the process becomes self-sustained ultimately leading to degradation of permafrost.

Threshold mechanisms are intrinsically probabilistic, and new type of permafrost model has been developed to address them. Unlike conventional models, it takes into account the small-scale spatial variability of soil, snow, and biophysiographic parameters in the calculations of the statistical ensemble representing potential states of permafrost under the prescribed conditions. Such model was used to assess changes in permafrost in Northern Eurasia under current and projected for the future climatic conditions.

Results indicate that 1–2˚C warming will lead to large-scale degradation of the frozen ground in the southernmost zone of sporadic permafrost. In continuous and discontinuous zones patchy effects will be manifested in vegetation changes at individual locations and subsequent local retreat of permafrost. Under sustained warming such changes will affect larger areas ultimately changing the landscape while local biophysiographic factors, i.e. soil, topography, slope, etc., will still play important role. Warming by more than 2˚C may lead to completely different vegetation patterns in the entire Arctic, with new biomes and taller and more productive spices replacing typical plant forms. Together with the direct warming effect it will make existence of near-surface permafrost virtually impossible in the modern sporadic and large part of the discontinuous zones, although at larger depths relict frozen ground will remain for centuries.

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