State-of-practice for synthesizing climate modelling data and risk-based estimation of geotechnical properties: a literature review

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Summary

There exists an increasing need for an improved understanding of thawing permafrost behaviour in the Arctic due to demand for infrastructure adaptation to climate change, anthropogenic impacts, and population growth. The Arctic is an important socio-economic zone that hosts communities, relies on linear infrastructure, and hosts industry in several sectors including energy, mining, forestry, and tourism. The Intergovernmental Panel on Climate Change (IPCC) advises that climate change impacts the Arctic more immediately and more severely compared to other regions (Meredith et al., 2019). Hazard assessment in the Arctic requires an understanding of how environmental conditions influence the engineering properties of frozen ground (Arenson et al., 2015). We present the state of practice for geotechnical characterization in Arctic regions including consideration of climate change. The process of developing forecasted permafrost hazard maps consists of three main components: 1) review of current climate models including methods for stochastic generation of forward-looking synthetic data, 2) geotechnical models for changes to soil properties resulting from changes to climate and ground temperature profile, 3) state-of-practice for incorporating climate impacts into geotechnical design and analysis to assist in developing mitigation and adaptation solutions. We conclude by summarizing and synthesizing information from the literature on climate change models and their influence on geotechnical properties, to suggest key areas of focus for future research and improvement to design practices for sustainable and resilient infrastructure.

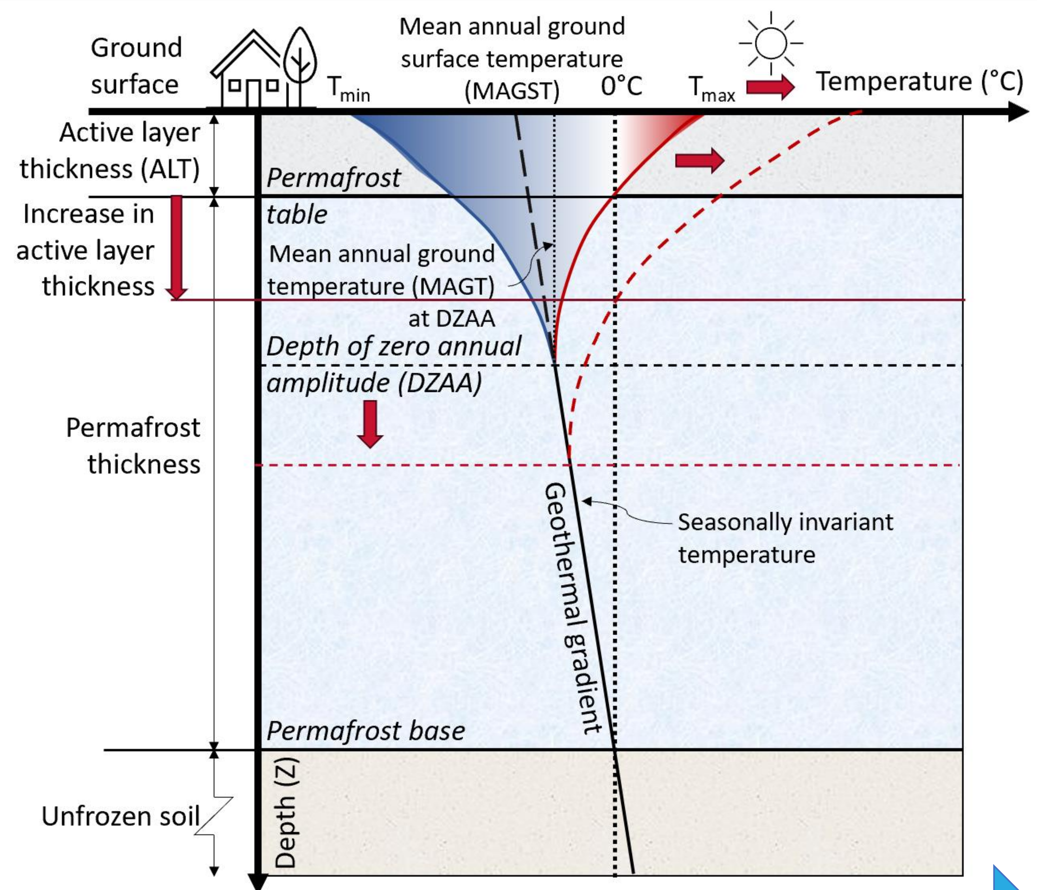


Figure 1. Thermal state of typical permafrost ground profile with the evolution of Active Layer Thickness (ALT) with an increase in ground surface temperature envelope due to climate change [adapted from Andersland & Ladanyi (2004)]. As ground temperature increases permafrost thaws, leading to reduced ground strength (Buteau et al., 2010), settlement (Hong et al., 2014), ground instability (Daanen et al., 2012), frozen ground creep (Aldaeef & Rayhani, 2017), increased runoff and flooding (Zheng et al., 2019), and undesirable impacts on socio-economic aspects of local communities and the environment (French, 2017).

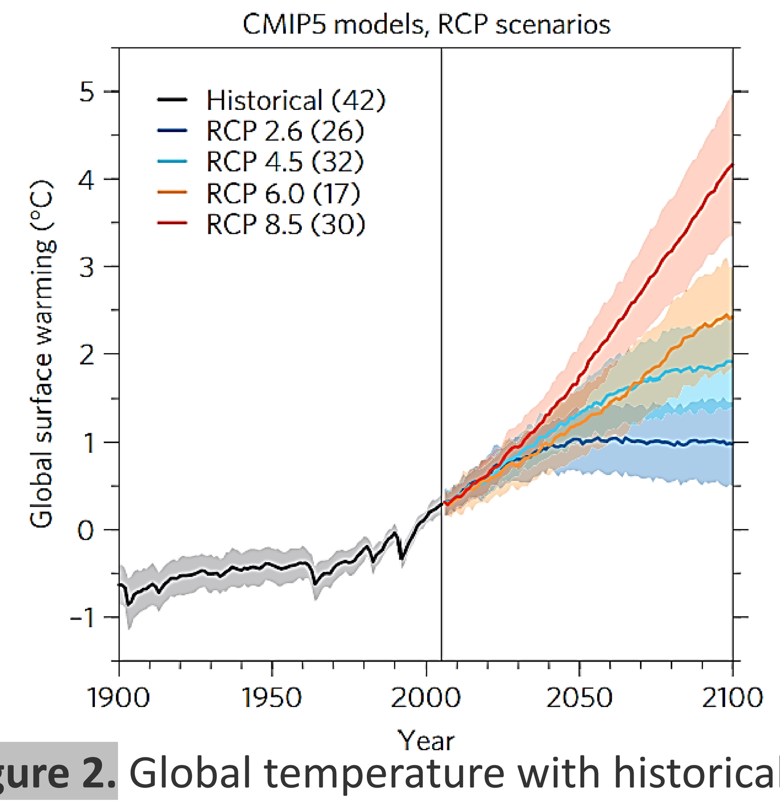
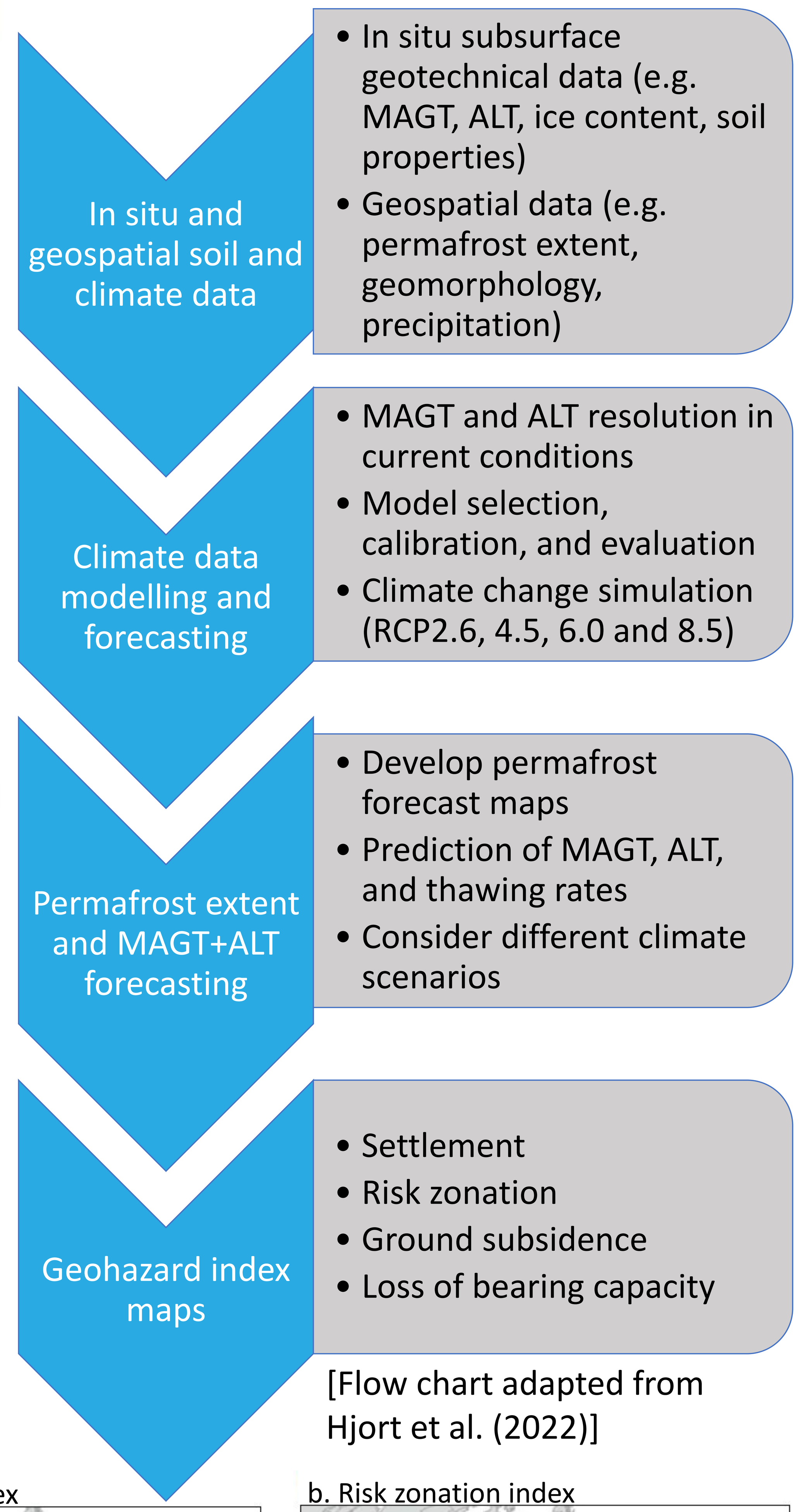
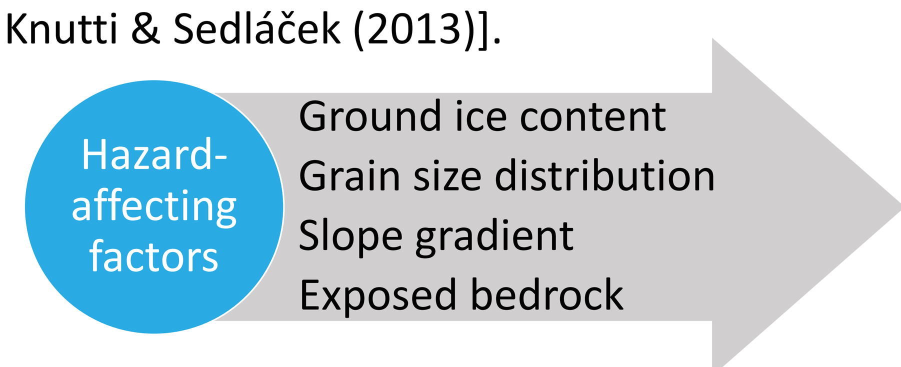


Figure 2. Global temperature with historical data and a set of Representative Concentration Pathways (RCP) based on greenhouse gas concentration (not emissions) trajectory adopted by the IPCC and run by CMIP5 [adapted from Knutti & Sedláček (2013)].



[Flow chart adapted from Hjort et al. (2022)]



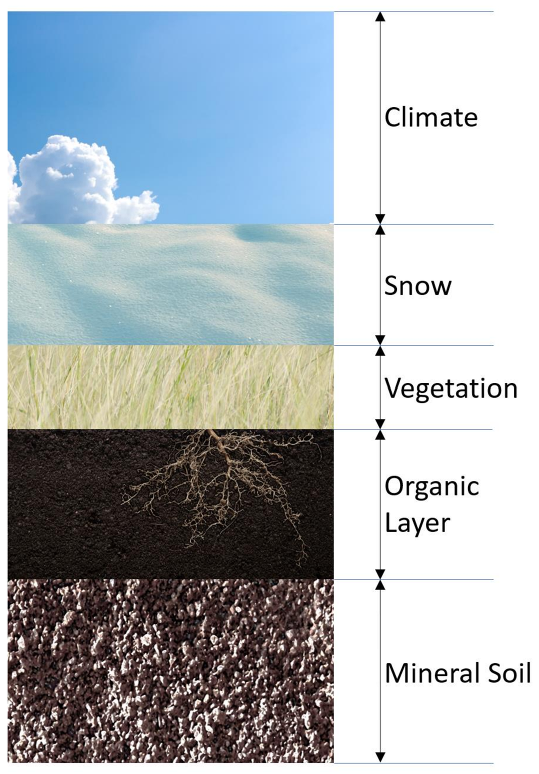


Figure 3. Layers for modelling changing permafrost properties are commonly used in forecasting hazard maps and geotechnical behavior of the ground [adapted from Streletskiy et al. (2012)].

Figure 4. Thawing permafrost may lead to ground subsidence as a result of thaw settlement due to phase change from ice to water and the loss of melted water draining away from the ground. Ground settlement from thawing permafrost is a major hazard for stability and safety of infrastructure (Ma et al., 2012), resulting in increased maintenance costs and remediation work to ensure structural integrity (Osterkamp & Burn, 2003). **Image Credit**: Leshyk, V.O. Center for Ecosystem Science and Society, Northern Arizona University (https://www2.nau.edu/schuurlab-p/).

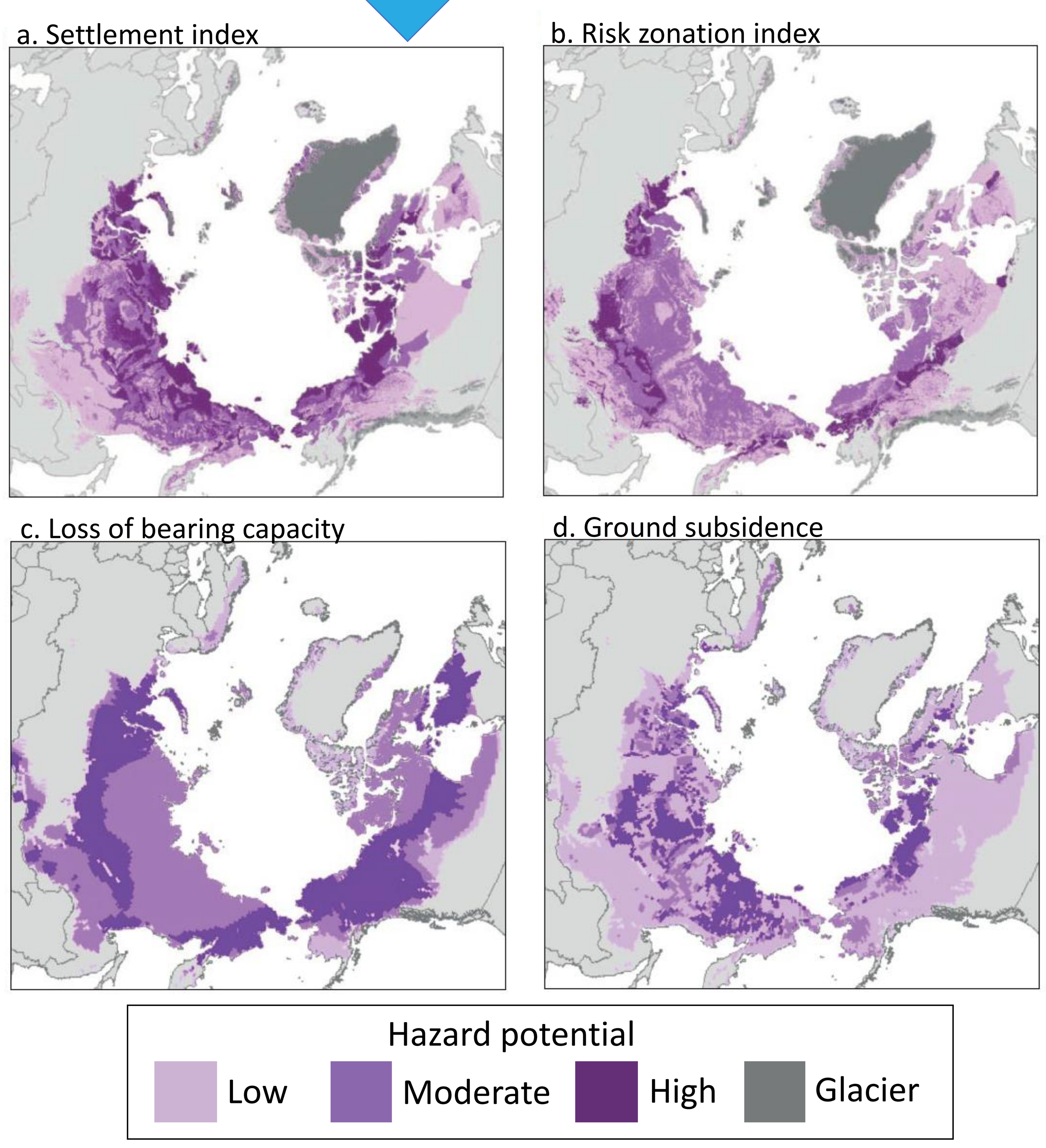


Figure 5. Forecasting permafrost hazards across the circumpolar area [adapted from Hjort et al. (2022) CC-BY 4.0].

a. Settlement index forecasted from the relative increase in ALT and ground ice content by the middle of the century (2041-2060) under RCP4.5 [adapted from Karjalaen et al. (2019) and Hjort et al. (2018)].
b. Risk zonation index [adapted from Karjalainen et al. (2019)] which also incorporates soil type and bedrock, soil frost susceptibility, ground ice content, and permafrost thaw potential.
c. Loss of structure-bearing capacity of the ground estimated based on the difference between 2005-2010 and forecasted 2050-2059 conditions under the RCP8.5 [adapted from Suter et al. (2019)].
d. Ground subsidence estimated based on the difference between 2005-2010 and 2050-2059 ground elevation under conditions RCP8.5 [adapted from Suter et al. (2019)].

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Concluding Remarks

Existing and future engineering projects in permafrost terrain should conduct local-scale infrastructure risk assessments, continuously monitor and incorporate corresponding mitigation measures to avoid infrastructure failure due to climate change to provide sustainable development in the Arctic region (Hjort et al. 2022).