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Statistical modelling of circumpolar permafrost: thermal and geomorphic sensitivities to climate change and societal implications

Olli Karjalainen

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Contents

Abstract

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Keywords: permafrost, ground temperature, active layer, geospatial data, statistical modelling, GIS, circumpolar, Arctic, pingo, ice-wedge polygon, rock glacier, geomorphology, geohazard, permafrost thaw, infrastructure risk, climate change.

One-fourth of the land area in the Northern Hemisphere is affected by perennially frozen ground, known as permafrost. The thermal conditions of permafrost govern complex geo- and ecosystems and provide support for Arctic cities and transportation infrastructure. Permafrost, however, is not permanent. Rather it is sensitive to the warming climate and human-induced disturbances. Recently, rapid degradation of permafrost landscapes has been observed across the Arctic. In addition to the local implications for the hydro-ecology, geo- and biodiversity and ground stability, permafrost degradation can affect the global climate through biogeochemical feedbacks. Ongoing changes to Arctic permafrost systems may have environmental and socio-economic repercussions on national and international scales.

The main aims of this thesis were to first examine how environmental conditions control the thermal and geomorphic permafrost characteristics on a circumpolar scale. Next, the sensitivity of permafrost to 21st century climate change was assessed. Lastly, high-resolution geohazard maps were produced and used to quantify the amount of infrastructure potentially at risk from thawing near-surface permafrost across the Northern Hemisphere. The thesis utilized statistical ensemble modelling techniques and geospatial datasets combined with comprehensive circumpolar observational datasets.

Based on the results, the studied permafrost characteristics were strongly controlled by and sensitive to current and future climatic conditions. The air temperature and rainfall had the most prominent contributions, while the effects of local terrain properties on a circumpolar scale were often found to be small. By the mid-century, the extent of near-surface permafrost may decrease by 34–47% depending on human-induced greenhouse gas emissions. Suitable areas for permafrost landform occurrence will similarly shrink, including regions of cold continuous permafrost. Quantifications of the infrastructure at risk indicated that around 70% of the studied engineering elements and four million people were located in areas of projected near-surface permafrost thaw. Moreover, one-third of all the infrastructure elements and nearly a million people situated in regions with high potential for permafrost degradation-related damage to the built environment.

In conclusion, circumpolar permafrost was projected to show extensive regionally distinct sensitivities to the ongoing climate change. Although most of the thermal and geomorphic impacts were projected to occur by the mid-century regardless of the climate-change scenario, it is argued that mitigating climate change could reduce the potential consequences for natural and human systems. In order to achieve a higher applicability of circumpolar-scale analyses on local scales, further developments in the availability and quality of global observational and geospatial data are required. Moreover, it is proposed that the pronounced nonlinearity found between climatic conditions and the studied permafrost characteristics should be carefully considered in future assessments.

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I Karjalainen, O., Luoto, M., Aalto, J. & J. Hjort (2019). New insights into the environmental factors controlling the ground thermal regime across the Northern Hemisphere: a comparison between permafrost and non-permafrost areas. *The Cryosphere*, 13, 693–707.

II Karjalainen, O., Luoto, M., Aalto, J., Etzelmüller, B., Grosse, G., Jones, B.M., Lilleøren, K.S. & J. Hjort. High potential for loss of iconic permafrost landforms in a changing climate (Submitted manuscript).

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IV Hjort, J., Karjalainen, O., Aalto, J., Westermann, S., Romanovsky, V.E., Nelson, F.E., Etzelmüller, B. & M. Luoto (2018). Degrading permafrost puts Arctic infrastructure at risk by mid-century. Nature Communications, 9, 5147.

Author contributions

	Original idea	Manuscript preparation	Data compilation and mining	Statistical analysis	GIS & geospatial analysis
Paper I	OK, ML, JH	OK, JA, JH, ML	OK, JA	OK, ML, JA, JH	OK, JA
Paper II	OK, ML, JH	OK, JH, ML, JA, BE, GG, BMJ, KSL	OK, JH, BMJ, GG, BE, KSL	OK, JH, ML, JA	OK, JH, JA
Paper III	JH, OK, ML, JA, VER, FEN, SW, BE	OK, JA, JH, ML, SW, FEN, VER, BE	OK, JH, ML, JA	JA, OK, JH, ML	OK, JA
Paper IV	ML, JH	JH, OK, JA, ML, SW, FEN, VER, BE	OK JH, ML, JA	JA, JH, ML, OK	OK, JA

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Oulu, January 2020

Olli Karjalainen

Glossary

Active layer = Seasonally thawed layer on top of permafrost.

Depth of zero annual amplitude (DZAA) = The depth at which the annual variation of ground temperature is < 0.1 °C.

Digital Elevation Model (DEM) = DEMs are digital representations of elevation on the Earth's surface. They can be used to compute topography parameters.

Ensemble modelling = The notion of an ensemble implies that combining multiple predictions with different statistical assumptions can yield an improved prediction and reduce uncertainty.

Equilibrium assumption = Here, equilibrium modelling assumes that a permafrost property is in thermal/geomorphic balance with surrounding environmental conditions (e.g. climate).

Generalized Additive Model (GAM) = A semiparametric extension of GLM, wherein model terms can be fitted nonparametrically using a smoothing function.

Generalized Boosting Method (GBM) = An ensemble learning method, in which multiple decision trees are fitted using boosting, i.e. the fits of previous fitted trees are considered sequentially to improve the accuracy of the final model.

Generalized Linear Model (GLM) = An extension of an ordinary linear regression, in which a combination of explanatory variables is related to a response variable by a link function.

Geohazard index = The geohazard index is a statistically formulated spatial representation of a geohazard, i.e. a potentially harmful geological or environmental condition.

Geospatial data = Data on a feature or phenomena assigned with location properties.

Ground ice = Frozen water content in the ground that can occur in various forms (e.g. segregated ice, massive ice or wedge ice).

Infrastructure = Engineering structures with permanent foundations.

Latent-heat exchange = The delay in phase change caused by the demand of extra energy needed to melt ice or freeze water.

Permafrost = Ground material, in which temperature stays at or below 0 °C for at least two consecutive years.

Permafrost degradation = Considered to occur when the permafrost temperature or the thickness of the active layer increases, or if permafrost thaws.

Permafrost landform = Permafrost landforms are geomorphic manifestations of ground ice processes.

Random Forest (RF) = An ensemble learning method that combines outcomes from multiple decision trees for an improved prediction. In contrast to GBM, each tree is fully grown, i.e. using all instances in randomly chosen subsets of predictors.

Representative Concentration Pathway (RCP) = RCPs depict atmospheric greenhouse gas concentration trajectories.

Statistical distribution modelling = Predictive modelling of the spatial distribution of a physical property based on a statistical model. In the modelling, observations of the property are statistically related to environmental conditions.

Thermokarst = Thermokarst is used to represent the process where the ground surface collapses (forming e.g. depressions, thaw slumps or thermokarst lakes) as the ground ice melts.

1 Introduction

Cold climates host a unique set of Earth surface processes behind the landscape evolution. *Permafrost*, or perennially frozen ground, is a thermally defined phenomenon that affects almost one-quarter of the Northern Hemisphere landmasses (Zhang *et al.* 1999). Soil or bedrock has permafrost if its temperature remains at or below 0 °C for at least two consecutive years (Permafrost Subcommittee 1988). Permafrost occurs in a delicate balance with climatic conditions, and thus reflects spatial patterns and dynamics in climatic conditions on seasonal to millennial time scales (Washburn 1980; Hinzman *et al.* 2005; Throop *et al.* 2012; Chadburn *et al.* 2017). The dynamic nature of the ground thermal regime suggests that permafrost is not permanent, which underlines the urgency of studying the state of permafrost in the rapidly changing Arctic climate.

A general increase in permafrost temperatures has been observed across the Northern Hemisphere during the last few decades (e.g. AMAP 2017; Romanovsky *et al.* 2018; Biskaborn *et al.* 2019; Meredith *et al.* 2019). The primary reason behind the observed trends is the increasing air temperature, but in some regions the snow thickness also exerts a definitive control on permafrost (Biskaborn *et al.* 2019). Consequently, near-surface permafrost in many regions has thawed (e.g. Smith *et al.* 2010; Nicolsky *et al.* 2017; Romanovsky *et al.* 2010, 2017). This development is likely to continue as the Arctic is warming more rapidly than the Earth on average in the twenty-first century (Hoegh-Guldberg *et al.* 2018; Schuur & Mack 2018). Alongside warming mean annual ground temperatures (MAGT), the depth of the seasonally thawed layer on top of permafrost, known as the *active-layer* thickness (ALT), has increased in many permafrost regions (Park *et al.* 2013; Luo *et al.* 2016; AMAP 2017; Romanovsky *et al.* 2018). In this thesis, MAGT and ALT are used to characterize the thermal state of permafrost, implying that increasing MAGT or ALT are indicative of *permafrost degradation*.

The climate-induced thermal dynamics of permafrost have not been uniform. In general, cold permafrost has been warming more rapidly than warmer permafrost (Smith *et al.* 2010; Romanovsky *et al.* 2010, 2017; Biskaborn *et al.* 2019). In contrast, the most momentous ALT increase has occurred in warm permafrost (Luo *et al.* 2016; AMAP 2017). The degradation of near-surface permafrost has the most dramatic consequences in areas with high *ground ice* content (Haeberli 1992; Rowland *et al.* 2010; Streletskiy & Shiklomanov 2016; Farquharson *et al.* 2019). When ice-rich permafrost thaws, *thermokarst* occurs and the ground may subside or become vulnerable to mass movements (Jorgenson *et al.* 2006; Kokelj & Jorgenson 2013; Schuur *et al.* 2015). Extensive and accelerating permafrost degradation has been observed recently across the Arctic (Kokelj *et al.* 2015; Liljedahl *et al.* 2016; Jorgenson & Grosse 2016; Farquharson *et al.* 2019; Lewkowicz & Way 2019) including the Tibetan Plateau (Yang *et al.* 2010; Ran *et al.* 2018). This development affects local geomorphological, hydrological and ecological conditions (Liljedahl *et al.* 2016; Brighenti *et al.* 2018; Schuur & Mack 2018), but also poses a threat to human constructions on ice-rich permafrost (Vincent *et al.* 2017; O'Neill *et al.* 2019; Turetsky *et al.* 2019) in lowland (Mackay 1972) and in mountain environments (Haeberli 1992; Beniston *et al.* 2018).

The impacts of permafrost degradation are by no means limited to the immediate high-latitude and altitude regions but affect the entire Earth through greenhouse gas and surface albedo feedback, for example (Schuur & Mack 2018; Moon *et al.* 2019; Turetsky *et al.* 2019). Bartsch *et al.* (2016) stress that the links between rapidly changing Arctic and the global climate system necessitate addressing the Arctic in its entirety rather than just regionally. Moreover, research on broad scales is vital because the circumpolar ground thermal regime may have different environmental controls than those described on site, local or regional scales (Riseborough *et al.* 2008; Grosse *et al.* 2016). Knight and Harrison (2013) argue that the responses of Earth surface systems to climate change remain poorly understood, notwithstanding that their functioning encompasses critical water and soil resources, ecosystem services, and biogeochemical climate feedback mechanisms. Moreover, despite abundant knowledge on the current observed permafrost dynamics, the effects and associated feedbacks on the geomorphology, ecosystems and *infrastructure* on local to global scales are still unclear (Grosse *et al.* 2011, 2016; Nicolsky *et al.* 2017; Oliva *et al.* 2018) and are limited by often coarse spatio-temporal resolutions of broad-scale analyses and climate-change projections (Riseborough *et al.* 2008; Etzelmüller 2013; Romanovsky *et al.* 2017). The statistical modelling approach applied in this thesis allows for utilizing high resolution *geospatial data* on environmental conditions and infrastructure elements, and thereby more explicitly than before, predicting local variations in permafrost characteristics and geohazards on a circumpolar scale.

Improved knowledge on the effects of climate change on permafrost regions is essential to facilitate adaptation measures for the likely significant impacts on natural and human systems in the Arctic (Hinzman *et al.* 2005; Oliva & Fritz 2018; Czekirda *et al.* 2019). Recent years have yielded a growing number of high-resolution circumpolar- to global-scale (hereafter broad-scale) assessments of the permafrost extent or thermal state (e.g. Gruber 2012; Park *et al.* 2016; Chadburn *et al.* 2017; Kroisleitner *et al.* 2018; Tao *et al.* 2018), but analyses using circumpolar-wise comprehensive observational datasets have remained relatively scarce until recently (e.g. Aalto *et al.* 2018a; Peng *et al.* 2018; Biskaborn *et al.* 2019; Obu *et al.* 2019). Geomorphological landforms which are unique to permafrost regions remain particularly understudied on broad scales. *Permafrost landforms* are physical manifestations of near-surface ground ice dynamics and they are thus sensitive to permafrost warming and thickening of the active layer (Michel 2011; Jorgenson *et al.* 2015).

This thesis aims to produce improved knowledge on the current state of the Northern Hemisphere permafrost and to assess the natural and societal implications of its projected near-future change. More precisely, the following research questions (RQ 1–5) are answered:

RQ 1: What are the key circumpolar environmental controls of thermal (MAGT and ALT) and geomorphic (pingos, ice-wedge polygons and rock glaciers) permafrost characteristics (Papers I and II)?

RQ 2: What are the thermal and geomorphic impacts of climate change on permafrost environments (Papers II and III)?

RQ 3: How and where does near-surface permafrost degradation pose hazards to Arctic communities and infrastructure (Papers III and IV)?

RQ 4: What is the magnitude of the potential near-surface permafrost degradation-related damage to infrastructure (Paper IV)?

RQ 5: What are the potential contributions of the used geospatial data-based statistical analyses to permafrost science?

To address these questions, this thesis examines the spatial variation of permafrost characteristics across the Northern Hemisphere by relating observational datasets on MAGT, ALT and permafrost landforms to globally comprehensive geospatial data on environmental conditions at 30 arc-second (< 1 km^2) spatial resolution. Climate-change scenarios are then used to assess the future thermal and geomorphic change in permafrost landscapes. The information gained is ultimately applied in assessments of potential societal climate change-induced consequences of degrading near-surface permafrost. Specifically, spatial datasets are employed to formulate *geohazard indices* and to quantify which infrastructure elements, natural resource extraction areas, or human settlements and populations are located in areas of permafrost thaw-related geohazards. The analyses are conducted in a statistical spatial modelling framework applying regression and machine learning-based techniques and ensemble modelling.

2 Study background

In this section, I present a literature-based conceptualization of the themes covered in the thesis and disclose relevant research gaps. First, the relationship between climate and permafrost characteristics (MAGT and ALT) are discussed. Second, the climatic sensitivity of permafrost is discussed in the context of climate change. Third, a brief review of the terrain properties (topography, soil properties and vegetation) mediating the permafrost-climate relationship on local spatial scales follows. Fourth, I describe the main characteristics of the studied permafrost landforms; pingos, ice-wedge polygons and rock glaciers. Finally, the human aspects of the impacts of degrading permafrost are problematized.

2.1 Preconditions for terrestrial permafrost

Permafrost forms when the annual net radiation balance is negative, i.e. the incoming solar radiation-derived energy affecting the ground is smaller than the outward heat flux from the Earth's surface (Lachenbruch & Marshall 1969; Péwé 1979; Nicolsky & Romanovsky 2018). Subsurface temperatures are closely connected to the atmospheric conditions affected by diurnal, seasonal, annual, decadal and millennial oscillations (Bodri & Cermak 2007; Harris *et al.* 2009). As the surface temperature signal propagates downwards, it affects the ground, attenuating progressively with depth (Huang *et al.* 2000; Bartlett *et al.* 2004). The amplitude of the annual temperature variation at a given depth depends on the thermal diffusivity of the ground (e.g. Bartlett *et al.* 2004; French 2007; Smith *et al.* 2010). The depth at which the annual variation of ground temperature is less than 0.1 °C is considered *the depth of zero annual amplitude* (DZAA, Fig. 1, Péwé 1979).

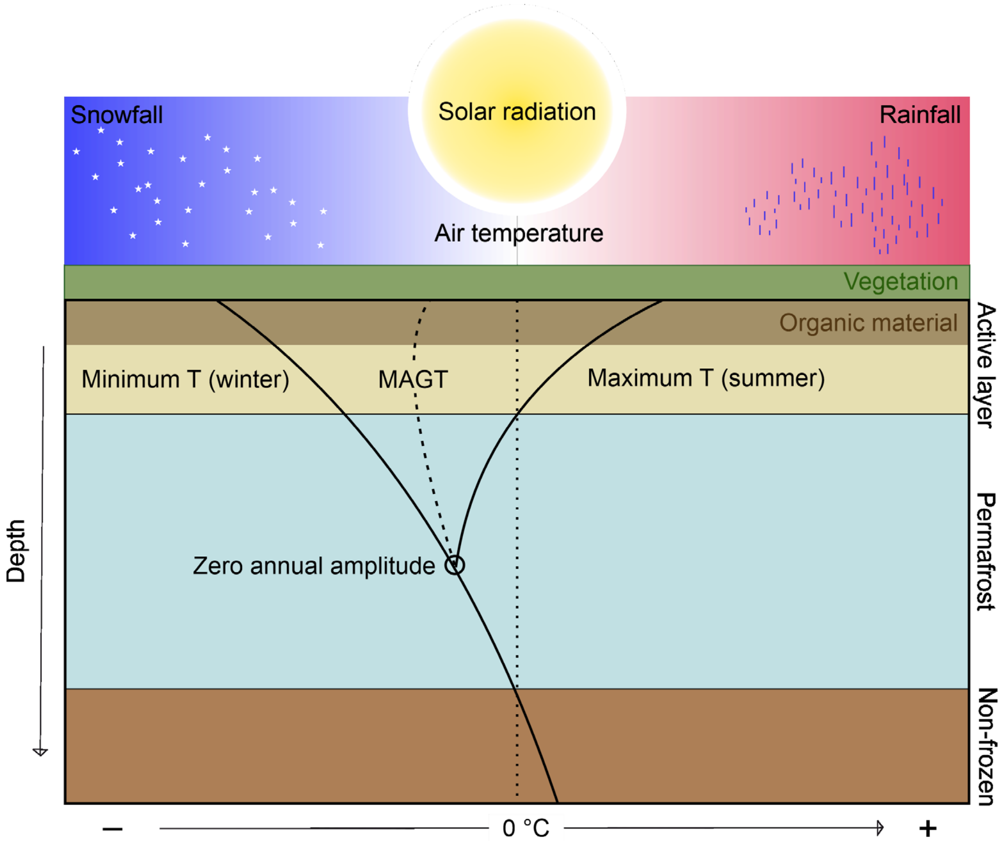


Figure 1. A simplified conceptual presentation of the permafrost thermal regime and the affecting factors. The black curves depict the hypothetical distribution of winter minimum and summer maximum ground temperatures (T) as a function of depth. The depth at which seasonal variations in ground temperatures fall to below < 0.1 °C is called the depth of zero annual amplitude. The hatched curve represents the mean annual ground temperature (MAGT).

2.1.1 Permafrost-climate relationship

The ground thermal regime is primarily controlled by mean annual air temperature (Smith & Riseborough 2002; Callaghan *et al.* 2011; Streletskiy *et al.* 2015). In general, warmer air temperatures result in a higher MAGT (Throop *et al.* 2012; Romanovsky *et al.* 2017) and greater ALT (Hinkel & Nelson 2003; Bonnaventure & Lamoureux 2013), but the local topography, ecosystem and soil conditions notably mediate the effect (Shur & Jorgenson 2007; Etzelmüller 2013; Aalto *et al.* 2018a, b). In addition, seasonal asymmetries in the air temperature-permafrost linkage are identifiable. Given the equal magnitude of change in winter and summer air temperatures, those during the winter have been suggested to exert a more direct influence on permafrost temperature (Smith & Riseborough 1996; Etzelmüller *et al.* 2011; Jones *et al.* 2016). ALT is essentially dependent on summer temperatures, and a higher annual temperature attributed to a warmer winter typically has a more negligible impact (Oelke *et al.* 2003; Melnikov *et al.* 2004; Zhang *et al.* 2005; Luo *et al.* 2016). Warmer winters can however affect the ALT through changing snow conditions and subsequent changes in hydrology and vegetation, for example (Park *et al.* 2013; Atchley *et al.* 2016).

The amount and seasonality of precipitation are controlled by the regional climate and further characterized by the local topography (Gruber *et al.* 2017). Rainfall affects the ground thermal regime by controlling both conductive and convective heat fluxes (Zhang *et al.* 2001; Westermann *et al.* 2010, 2011; Marmy *et al.* 2013; Slater & Lawrence 2013). For example, Melnikov *et al.* (2004) argued that heavy summer rains cause warming and a greater ALT, but that in the autumn rain can cool the ground and suppress the thickening of the active layer also in the next thawing season due to the increased ice content at the base of the active layer. Kokelj *et al.* (2015) stressed that increases in rainfall are anticipated to have a significant impact on permafrost geomorphology.

Snow acts as an insulating agent that increases temperature differences between the air and ground (e.g. Zhang *et al.* 1996, 2001; Stieglitz *et al.* 2003; Slater *et al.* 2017). This is because snow has a low thermal diffusivity, and thus it can mute some of the effects of low air temperatures (Bartlett *et al.* 2004). The degree at which the ground heats or cools, and at what magnitude, depends on the timing and duration of the seasonal snow cover (Zhang 2005, Westermann *et al.* 2011). The insulation effect saturates when the snow thickness reaches 40–50 cm (Zhang 2005; Slater *et al.* 2017). In addition, snow exerts an important meltwater input (Beniston *et al.* 2018). With all of the effects taken into consideration, snow cover increases ground temperatures (Smith & Riseborough 1996; Zhang *et al.* 1997; Osterkamp 2007; Ekici *et al.* 2015), but the magnitude of the effect on the deeper soil depends on additional factors, such as the ground material, ALT and the presence of moisture (Romanovsky *et al.* 2010; Throop *et al.* 2012). In certain regions of discontinuous and sporadic permafrost, the absence of snow cover can be a key factor for permafrost development (Seppälä 1997; Zhang 2005; Smith & Riseborough 2002; Biskaborn *et al.* 2019). According to Frauenfeld *et al.* (2004), deep snow during the preceding winter can contribute to the ALT in two ways: causing higher spring and summer moisture and inheriting a shallower freeze depth. Soil temperatures also show pronounced spatial variability related to regional climate-driven snowpack properties, such as density and moisture (Wang *et al.* 2016).

2.1.2 Climatic sensitivity of permafrost

A consensus has formed that the magnitude of future climate warming will greatly affect the temperature and the extent of permafrost (e.g. AMAP 2017; Biskaborn *et al.* 2019; IPCC 2019). Depending on the climate scenario, suitable conditions for permafrost have been predicted to disappear from the present discontinuous zone (assuming medium human-induced greenhouse gas emissions) or retreat to encompass mostly high-Arctic conditions and continental Siberia (high emissions) by 2100 (Slater & Lawrence 2013). Hence, reducing emissions could help mitigate the impacts of the warming on permafrost. Chadburn *et al.* (2017) and Wang *et al.* (2019) concluded that attaining the targeted 1.5 °C global warming (compared to the pre-industrial period 1850–1900) proposed in the Paris Agreement (UNFCCC 2015) could prevent ~2 × 10^6 km^2 of permafrost from thawing when compared to 2.0 °C warming (cf. Guo & Wang 2017a). Wang *et al.* (2019) simulated that 1.5 °C warming would be reached as soon as in the 2020s regardless of the used emission trajectory. According to the special report by the Intergovernmental Panel on Climate Change (IPCC 2019), the mean surface air temperature over land areas (excluding oceans) had already reached this limit by 2006–2015. It has already been earlier recognized that the focus should be set for adaptive policies to mitigate the negative outcomes of warming climates (Knight & Harrison 2013; AMAP 2017).

The responsiveness of the ground to climatic conditions depends on its initial thermal state, predominantly the presence or absence of permafrost. In permafrost conditions, the active layer acts as a buffer impeding the translation of atmospheric temperatures to deeper permafrost (Fig. 1, Osterkamp & Romanovsky 1999; Throop *et al.* 2012; Luo *et al.* 2016). In non-frozen soils the effect of the climate signal is more direct (Kurylyk *et al.* 2014; Ekici *et al.* 2015). Notwithstanding, varying sensitivities exist inside the permafrost domain. Shur and Jorgenson (2007), for example, classified permafrost types based on the interactions of climatic and ecological processes involved in permafrost formation and degradation. According to them, the development of continuous permafrost is mostly driven by climate, while the effects of ecosystem characteristics gain importance towards warmer permafrost regions.

2.1.3 Terrain properties

On local to regional scales, the topography exerts control over the air temperature as a function of elevation, solar radiation and snow transport (Harris *et al.* 2003). Moreover, the terrain curvature and slope regulate water distribution in the soils (e.g. Etzelmüller *et al.* 2001), which is inherently dependent on the cohesive and water retaining properties of the soil. The presence of water in the ground either in liquid state or frozen, i.e. as ground ice, is a key factor affecting the response of permafrost thermal regimes to climatic changes (e.g. Riseborough 1990; Kurylyk *et al.* 2014). More precisely, permafrost warming is slowed by the higher demand of energy to melt ground ice in the active layer (i.e. *latent-heat exchange*, Riseborough 1990). The autumnal re-freeze, in turn, is delayed due to the latent heat present in the liquid water in the soil (Romanovsky & Osterkamp 2000; Romanovsky *et al.* 2010).

The principal heat transfer mode between geothermal and atmospheric heat in permafrost is conduction (Smith & Riseborough 1996). Convective heat transport (by moving water or water vapor) is smaller owing to the limited water movement in frozen soils (e.g. Lachenbruch & Marshall 1986; Harris *et al.* 2009; Weismüller *et al.* 2011) yet it is still significant in certain conditions (Kurylyk *et al.* 2014, Yin *et al.* 2017; Nicolsky & Romanovsky 2018). The annual air temperature signal attenuates at shallower depths in soil compared to bedrock due to differences in the thermal conductivity (Smith *et al.* 2010). Furthermore, coarse-grained soils have greater conductivity than fine-grained soils (e.g. Riseborough 1990; Callaghan *et al.* 2011) and peat is less conductive than mineral soils in all ice/liquid/gas saturation states (Atchley *et al.* 2016).

Soils with a high organic carbon content have low conductivity in a dry state, whereas when wet they can transfer energy effectively (Kane *et al.* 2001). Especially frozen, wet organic soils can have a high volumetric ice content and high conductivity, which allow for effective cooling of the ground during cold weather. In the summertime, dry organic soil acts as a weakly conductive insulator that prevents the ground from warming (Kane *et al.* 2001). Attributed to this asymmetrical heat flow, permafrost may persist in isolated patches with a high organic content outside discontinuous permafrost areas (Shur & Jorgenson 2007; Harris *et al.* 2009). The impact of soil organic matter on the thermal diffusivity of soils has been shown to also markedly affect the broad-scale permafrost dynamics (Lawrence *et al.* 2008; Zhu *et al.* 2019). Schuur and Mack (2018) suggested that soil organic carbon should be considered as an integrative part of permafrost (along with the temperature and ground ice content) in dictating its response to climate change and further consequences for ecosystems and society.

During the snow-free season, the vegetation layer controls the energy and water exchange between the ground and the atmosphere (Zhang *et al.* 2003; Ekici *et al.* 2015). Vegetation affects the ground thermal regime by intercepting the snowfall and solar radiation (Smith *et al.* 2010; Woo 2012), reducing the summer heat flux and retaining the insulating snow layer during the winter (Walker *et al.* 2003; Zhang 2005; Luo *et al.* 2016), and cooling the ground surface and controlling the water balance through evapotranspiration (Smith & Riseborough 1996, 2002; Jorgenson *et al.* 2010; Gruber *et al.* 2017).

In a recent global-scale study De Frenne *et al.* (2019) demonstrated that differences between the temperatures under forest canopies and adjacent open areas can exceed the magnitude of global warming over the last century. Although the study was conducted in non-permafrost forests (boreal to tropical biomes), the magnitude of the found temperature offsets suggests that future assessments of fine-scale permafrost variability could benefit from considerations of understory microclimates across the vast taigas in Siberia and North America. Local-scale studies have indeed demonstrated that in near-zero MAGT conditions the snow retaining effect (Sladen *et al.* 2009) or insulating and moisture retaining effects of the vegetation layer *per se* (Yin *et al.* 2017) can determine whether permafrost is present or absent. Another local determinant of thermal ground conditions is the presence of open water. Water bodies in permafrost regions induce talik formation (unfrozen layer in permafrost) and can account for ground temperature anomalies of several degrees centigrade in their vicinities (Jorgenson *et al.* 2010; Woo 2012).

2.2 Permafrost landforms

Permafrost landforms can be considered to be a subcategory of a wider group of periglacial landforms, which occur also in regions of seasonally frozen ground, and thus do not require permafrost to develop. In this thesis, three iconic landforms encountered in permafrost environments across the Northern Hemisphere were studied. Pingos are intrapermafrost ice-cored mounds that form by two principal processes. Hydrostatic pingos typically form due to the aggradation of ice lenses in low-lying drained lake basins, while more topographical relief is associated with hydraulic pingos that depend on water moving under a hydraulic gradient (Mackay 1973; Jones *et al.* 2012, Fig. 2a). The majority of pingos occupy circum-Arctic lowlands (Grosse & Jones 2011). Ice-wedge polygons are ubiquitous in unconsolidated soils in the continuous permafrost zone (Bernard-Grand'Maison & Pollard 2018, Fig. 2b). Ice wedges form by cyclical freezing of melt waters in frost cracks that form during winter cold spells (Washburn 1980). Rock glaciers, found in the periglacial belt of all major mountain environments (Barsch 1988), consist of a mixture of ice and poorly sorted debris that flows under gravity due to internal deformation (Barsch 1988; Berthling 2011, Fig. 2c). Multiple rock glacier typologies based on morphology, activity or genesis, for example, have been proposed but often two schools are differentiated based on the origin of a rock glacier. The permafrost creep school (e.g. Haeberli *et al.* 2006) assumes that rock glaciers aggregate ice as they form from loose talus or other slope material, whereas the other view is that ice is derived from a glacier that becomes mixed with debris and eventually forms a rock glacier (Whalley & Martin 1992). In this thesis, all types of rock glaciers, apart from debris-covered glaciers (e.g. Anderson *et al.* 2018), were considered.

Most studies of permafrost landforms have been conducted on local to regional scales involving aspects such as detailed follow-up studies of single landforms (see Mackay 1972; Humlum & Christiansen 2008) or descriptive (sometimes statistical) assessments of the observed environments for a set of landforms (see Grosse & Jones 2011; Ran & Liu 2018). Broad-scale efforts are less frequent except Grosse and Jones's (2011) spatial data analysis of pingos across northern Asia. Recently, regional inventories of rock glaciers, in particular, have become increasingly abundant due to the increased availability of high-resolution remote sensing-based data products and imagery provided by Google Earth, for example (Schmid *et al.* 2015; Ran & Liu 2018; Du *et al.* 2019). A comprehensive review of global inventory works concluded that at least 73,000 rock glaciers exist globally (Jones *et al.* 2018). Grosse and Jones (2011) estimated that all types of pingos considered there are at least 11,000 pingos on Earth. Broad-scale modelling assessments, however, have been hindered by the lack of homogenized datasets of landform occurrences. Moreover, (predictive) distribution modelling studies of pingos, ice-wedge polygons and rock glaciers, are lacking apart from a few regional-scale studies (e.g. Brenning *et al.* 2007; Marcer *et al.* 2017; O'Neill *et al.* 2019).

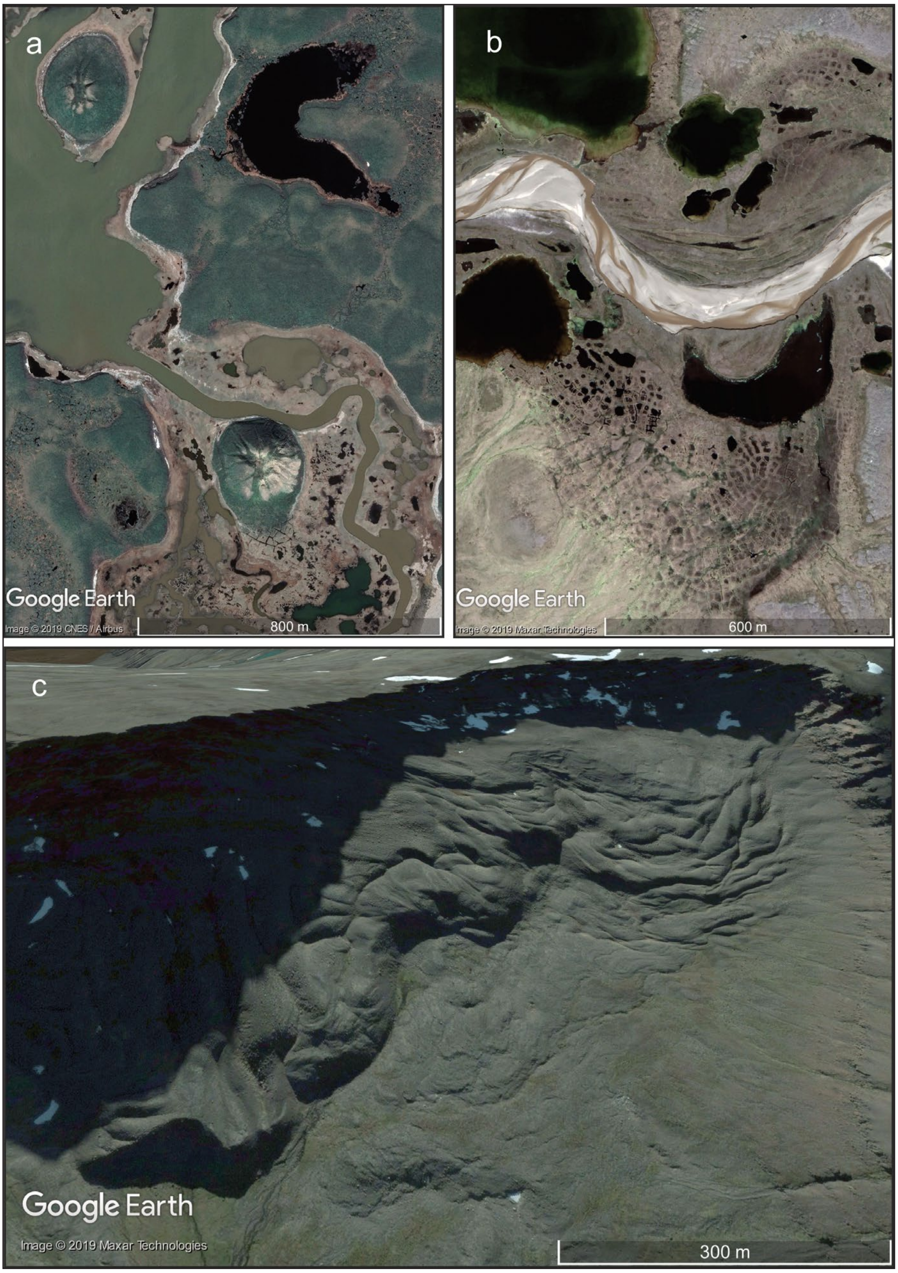


Figure 2. Examples of the studied landforms in satellite imagery. Two large pingos (a) on the Arctic Ocean coast near Tuktoyaktuk, Canada (69.399 °N, 133.079 °W, Image © Google Earth, CNES/Airbus), ice-wedge polygons (b) at various stages of degradation on the Yamal Peninsula (72.354 °N 72.555 °E, Image © Google Earth, Maxar Technologies), and rock glaciers (c) on Disko Island, Greenland (69.417 °N, 53.926 °W, Image © Google Earth, Maxar Technologies).

2.3 Human activity and permafrost

The adverse effects of permafrost aggradation and degradation on buildings or transportation infrastructure are by no means a new phenomenon. Human settlements and the utilization of natural resources in the Arctic have long been affected by ground ice dynamics, and adaptation measures been developed historically (Mackay 1972; Péwé 1979; Koutaniemi 1985; Shiklomanov 2005). Recently, the intensifying socio-economic activity in the Arctic has evolved into a growing concern for the local and global consequences that rapidly warming permafrost may have in the near future (Callaghan *et al.* 2011; Vincent *et al.* 2017; IPCC 2019). This amusingly illustrates the development of cryospheric science during the past decades, given that in the 1960s research of underground ice according to Mackay (1972: 12) was denoted by many as a *"scientific luxury, interesting, but of little concern to the affairs of modern man"*. This view, according to Mackay (1972), rapidly changed after the early oil extraction industry was faced with the problems associated with melting ground ice. The vulnerability of the infrastructure to thawing permafrost, however, had been recognized in early literature in Russian (Sumgin 1927) and Alaskan contexts (Muller 1947).

Notwithstanding the remoteness and harsh climate, the permafrost regions in the Northern Hemisphere are home to millions of people and possess vast amounts of natural resources, such as hydrocarbon deposits (Streletskiy & Shiklomanov 2016; Badina 2017; Streletskiy *et al.* 2019). Assessing the wide-ranging implications of change in the Arctic necessitates an integrated approach that considers the consequences and interrelationships between multiple natural and societal aspects (Vincent *et al.* 2017; Schuur & Mack 2018). In this thesis, I adopt a systematic approach, in which permafrost is considered a regulator of the impacts of climate change to infrastructure. The system, however, has other multidirectional relationships, e.g., the direct effects of the infrastructure on local permafrost degradation or those of biogeochemical feedback mechanisms (e.g. greenhouse gas emissions from thawing permafrost) on the global climate, which are beyond the analytical scope of the thesis.

Despite the growing global relevance of the Arctic and abundant Arctic-wide, local evidence of permafrost degradation-related damage to infrastructure (e.g. Grebenets *et al.* 2012; Doré *et al.* 2016; Shiklomanov *et al.* 2017), the spatial distribution of hazards on a circumpolar scale is insufficiently known. Among the first mapping efforts, Nelson *et al.* (2001, 2002) formulated a geohazard index which is applicable to assessing ground settlement due to an increasing ALT across the Northern Hemisphere. The settlement index and its remakes (Anisimov & Reneva 2006; Guo & Sun 2015; Guo & Wang 2017a), however, only considered one type of geohazard and were highly generalized and coarse in their spatial resolution. Thus, they were of limited value to address within-region variability concerning the hazard potential. In addition, permafrost degradation-related risks to specific infrastructure elements or population centers have not been quantified on a circumpolar scale.

3 Study area

This thesis focuses on the Northern Hemisphere land areas north of the 30th latitude (Fig. 3). The main focus is on the permafrost domain but non-permafrost regions, parts of them characterized by seasonal freezing (Zhang *et al.* 2003), are also addressed for methodological (see Papers III-IV) and comparative (Paper I) reasons. The extensive areas of high-altitude permafrost in the Tibetan Plateau and in other mid-latitude mountain areas are here considered as parts of the circumpolar permafrost domain. Permafrost is typically classified based on its lateral extent. The zone of continuous permafrost, by definition affecting more than 90% of an area (Zhang *et al.* 1999), characterizes the coldest areas most extensively found in Russia, Canada and Alaska (Fig. 3). In northern Alaska, the permafrost thickness can reach depths of ~500 and up to 1,500 m in northern Siberia (Washburn 1980; Bodri & Cermak 2007). As environmental conditions become less suitable for permafrost, its extent becomes discontinuous (50–90% cover) and sporadic (10–50%). Outside these zones isolated patches of permafrost (< 10%) occur in locations with suitable microclimates (e.g. high elevations, ice caves) or soil/vegetation conditions that allow for permafrost to persist under warmer conditions (e.g. palsa mires, Seppälä 1997; Luoto & Seppälä 2002; Shur & Jorgenson 2007). All zones considered; permafrost covers ~23 x 10^6 km^2 (24%) of the exposed land areas in the Northern Hemisphere (Zhang *et al.* 1999).

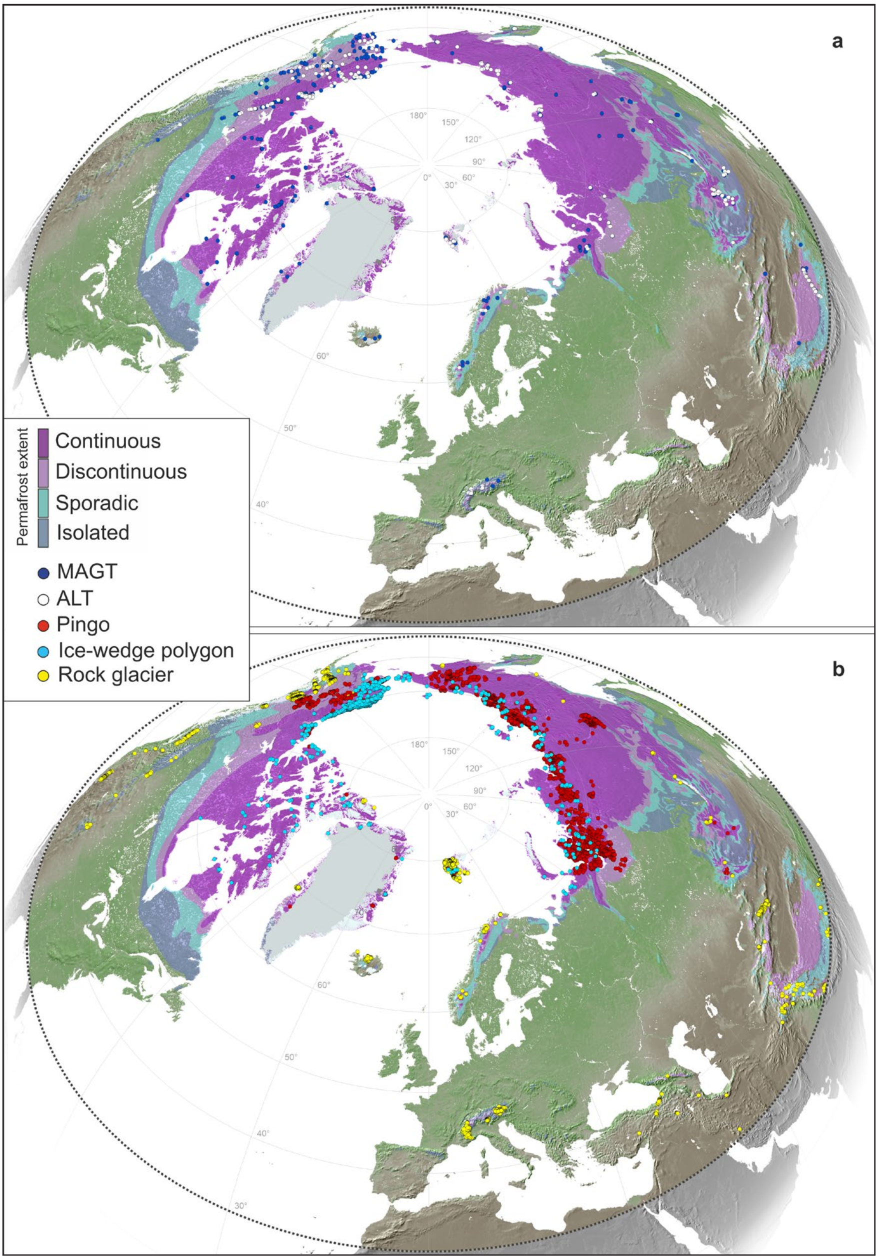


Figure 3. The Northern Hemisphere study area north of 30^{th} latitude and the used observational datasets. Locations for the compiled mean annual ground temperature (MAGT, n = 797) and active-layer thickness (ALT, n = 303) observations are displayed in panel a. The permafrost landform occurrences included 9,709 pingos, 861 ice-wedge polygons and 4,035 rock glaciers (b). The permafrost domain is shaded by its extent after Brown *et al*. (2002).

4 Materials and methods

4.1 Response data

4.1.1 Observations of mean annual ground temperature and active-layer thickness

The MAGT and ALT observations (Fig. 3a) used in Papers I, III and IV were compiled from previous databases, research articles and maps (Supplementary Tables 1–2 in Paper III). In Paper I, the MAGT at or below 0 °C (representative of permafrost) and MAGT above 0 °C (non-permafrost) were analysed separately. The preconditions for the included MAGT and ALT observations implied that they were 1) not disturbed by geothermal or anthropogenic heat sources, recent fires or large water bodies in the immediate vicinities, 2) recorded during the study period (2000–2014), and 3) had an adequate locational accuracy in order to comply with the used geospatial data at a 30 arc-second resolution. If more than one observation occupied the same grid cell, a median value was used. Additional dataset-wise steps were taken to ensure that the field observations were comparable across the study area and are described below.

The MAGT can be determined for any observed depth using temperature measurements from boreholes, for example. The temporal resolution of the used ground temperature data varied between year-round hourly records to single once-in-a-year observations. Continuous records were averaged over a year, and when single observations were used it was ensured that the given depth was not affected by intra-annual temperature fluctuations. To address spurious measurements, ground temperatures at or near the DZAA (Section 2.1) in near-surface permafrost (on average 12.5 meters below the ground surface) were utilized. This delineation was necessary to balance between 1) filtering out inter-annual fluctuations occurring in the top soil layers (Romanovsky *et al.* 2002), 2) ensuring that the ground thermal regime is in balance with current climatic conditions on a decadal time scale (Romanovsky *et al.* 2007), and 3) thus being responsive to projected changes in the climate in the studied future periods (2041–2060 and 2061–2080). It is important to note that even though deep permafrost occurring at depths of several tens to hundreds of meters can persist in a changing climate (Lachenbruch & Marshall 1986; Huang *et al.* 2000), near-surface layers are anticipated to show quick and significant responses to even temporary decadal-scale air temperature increases (Guo & Wang 2017b; Zhang *et al.* 2018a).

Field measurements of active-layer thickness are done either by physically probing the ground at the time of maximum thaw or reading the exact depth of the thaw from year-round installed thaw tubes (Brown *et al.* 2000). In addition, the thaw depth can be inferred from soil temperature profiles; the ALT value is a product of an interpolation between the nearest two measurements above and below the depth of the maximum thaw

(Nelson & Hinkel 2004). Comparability between the ALT measurements derived from different methods and at different locations was achieved by using values that represent the maximal annual thaw recorded during late summer to autumn (Hinkel & Nelson 2003; Bonnaventure & Lamoureux 2013). Figure 4 presents an overview of the performed research from data preparation to statistical analyses, geohazard index formulation and quantifications of the infrastructure at risk.

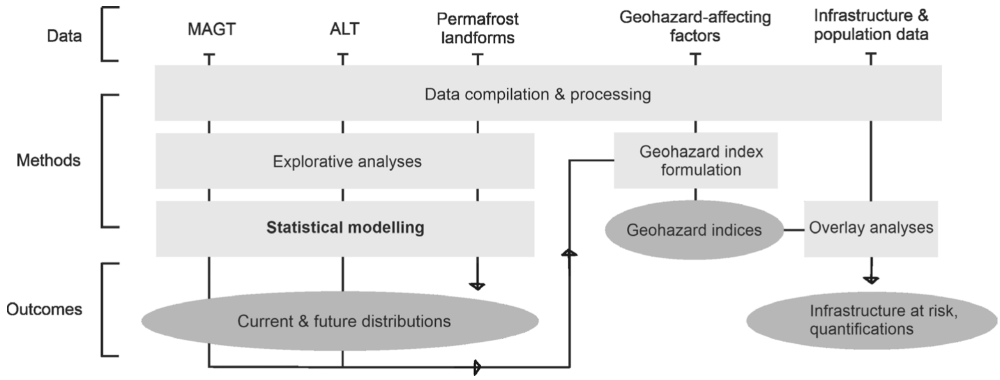


Figure 4. The study design scheme presenting the used data, methods (light grey boxes) and outcomes (dark grey ovals) of the performed analyses. To ensure globally comparable observational data on the mean annual ground temperature (MAGT), active-layer thickness (ALT), permafrost landforms and infrastructure and population data, criterion frameworks were developed and applied (see text). Explorative analyses included assessments of sample statistics and bivariate correlations in the modelling data. Statistical modelling was performed applying ensembles of four modelling techniques. The produced predictions of the MAGT and ALT, together with additional geospatial data on geohazard-affecting factors, were applied in geohazard index formulation. Finally, the geohazard indices were employed in overlay analyses, in which the susceptibility of the infrastructure and population to near-surface permafrost degradation-related geohazards was quantified.

4.1.2 Permafrost landform observations

In order to perform a circumpolar modelling of permafrost landform distributions, datasets of pingo, ice-wedge polygon and rock glacier occurrences (Fig. 3b) were compiled from available sources (Supplementary Table 3 in Paper II). In the compilation, the primary types of landforms were grouped together, although in some cases, the geomorphic processes behind their formation may differ (e.g. Harris 1981; Knight *et al.* 2019). Similarly to MAGT and ALT data, only one observation was assigned for each grid cell to avoid pseudoreplication (Hurlbert 1984). By aiming to include all the documented occurrence areas I sought to minimize sampling biases, e.g., observations clustered only in well-studied and accessible regions. However, extensive under-sampled regions remained. Overall, these data are suggested to be the most geographically comprehensive spatial data compilations of pingos, ice-wedge polygons and rock glaciers covering the Northern Hemisphere.

Method-wise, modelling geomorphic landforms (presence-absence) and MAGT and ALT (continuous response) is similar, but some geomorphological discourses can be attached to the study of landforms. First, landforms are simplifications of their natural environment where they are highly variable in form and occur in continuums of landscape elements. Thus, they are a product of classification. For example, among the contested discourse about rock glacier typologies (e.g. Barsch 1988; Whalley & Martin 1992) there is still some ongoing discussion on the continuum of glacier–debris-covered glacier–rock glacier development (e.g. Anderson *et al.* 2018; Jones *et al.* 2019a; Knight *et al.* 2019). So far, no canonical thresholds to delineate rock glacier types exist, although new classification schemes based on the surface movement dynamics, for example, have been proposed (Knight 2019). Similar discussions have lingered around pingos, which are usually thought to form because of two different groundwater pressure mechanisms (Mackay 1973, 1998). A process-based classification in practice, however, is often not feasible as both mechanisms can occur simultaneously (Worsley & Gurney 1996; Gurney 1998).

To confront such hindrances, Paper II assumed a concept of equifinality whereby similar landforms are thought to result from a varying set of processes and initial conditions (Slaymaker 2004). Such generalizations were needed in order to achieve comprehensive modelling datasets on a circumpolar scale, i.e., to cover the entire gradient of environmental conditions occupied by known landform occurrences. Another central concept to the study of future distributions is that of uniformitarianism. James Hutton proposed that the Earth's geological history can be explained in terms of natural forces acting today, and further, that the same applies for the future (Hutton 1788). In this thesis, the view was reflected in an assumption that past climate-induced shifts in landform distributions, as demonstrated by the remnants of pingos and ice-wedge patterns across currently temperate climate regions (Vanderberghe & Pissart 1993; Mackay 1998; Vandenberghe *et al.* 2014), would be anticipated in future changing climates.

4.2 Geospatial data

Numerous web-based data depositories and data infrastructures have made geospatial data increasingly available (Dowman & Reuter 2017). In this thesis, geospatial data constituted digital data layers (raster and vector) that could be processed with geographical information system (GIS) software; herein primarily ArcGIS (ESRI 2015), R (R Core Team 2015) and the System for Automated Geoscientific Analyses (SAGA GIS, Conrad *et al.* 2015). Given the marked reliance of the statistical analyses on correlations in the data (Marmion *et al.* 2009), care had to be taken to choose the most appropriate predictors for each response (Austin *et al.* 2006; Hjort & Luoto 2013). Based on the literature, the aim was to involve all physically relevant predictors of sufficient spatial resolution and coverage (Table 1). Apart from ground ice content data (Brown *et al.* 2002), originally at 12.5 km spatial resolution, all predictors had a native resolution of 30 arc seconds (< 1 km^2 grid cell size) or finer, and were resampled to 30 arc second resolution prior analyses. The geographical extent of all the predictors was limited at the 30^{th} latitude.

Table 1. The geospatial and infrastructure data used in individual papers. The abbreviated dataset acronyms are: Global Meteorological Forcing Dataset (GMFD), United States Geological Survey (USGS) Shuttle Radar Topography Mission (STRM) Digital Elevation Model (DEM), Global Multi-resolution Terrain Elevation Data (GMTED), International Permafrost Association (IPA), European Space Agency Climate Change Initiative (ESA CCI) and Moderate Resolution Imaging Spectroradiometer (MODIS).

Original dataset	Derived parameters	Used in Papers	Original data citation
WorldClim v1.4	Freezing degree-days Thawing degree-days Snowfall Rainfall	I–IV	Hijmans *et al.* 2005
GMFD	Climate reanalysis adjustment parameters	I, III–IV	Sheffield *et al.* 2006
USGS SRTM DEM	Potential incident solar radiation (after McCune & Keon 2002) Slope gradient	I, III–IV III–IV	United States Geological Survey 2004
GMTED	Potential incident solar radiation (after McCune & Keon 2002) Slope gradient Topographical Wetness Index (after Böhner & Selige 2006)	II	Danielson & Gesch 2011
SoilGrids1km	Soil organic carbon content Coarse sediment content Fine sediments content	III–IV	Hengl *et al.* 2014

SoilGrids250m	Soil organic carbon content Coarse sediment content Fine sediments content	I–II	Hengl *et al.* 2017
	Soil and sediment deposit thickness	III–IV	Pelletier *et al.* 2016
IPA	Volumetric ground ice content	III–IV	Brown *et al.* 2002
ESA CCI Water Bodies v4	Coverage of water bodies	II–IV	Defourny 2016
MODIS Terra	Normalized Difference Vegetation Index	I	Didan 2015
OpenStreetMap	Roads Railways Oil and gas pipelines Buildings Industrial areas Populated settlements	IV	OpenStreetMap Contributors 2016, www.openstreemap.org
OurAirports	Airports and airfields	IV	OurAirports.com
Rosnedra	Hydrocarbon extraction areas in Russia	IV	gis.sobr.geosys.ru
Gridded Population of the World (GPW v4)	Human population	IV	Center for International Earth Science Information Network (CIESIN) (2016)

4.2.1 Current and future climates

Attributed to the seasonal asymmetries in the response between atmospheric and ground thermal regimes (see Section 2.1.1), winter and summer air temperatures and precipitation were considered separately. Several previous studies have demonstrated that indices representing the length or magnitude of the thawing and freezing seasons are often more suitable for permafrost modelling than mean annual air temperature (e.g. Zhang *et al.* 1997; Harris *et al.* 2009; Smith *et al.* 2009). Four climatic parameters; freezing and thawing degree days (FDD and TDD, °C-days), and the snow- and rainfall estimated from monthly air temperature averages were computed from gridded data on interpolated monthly climate surfaces in the WorldClim database (Hijmans *et al.* 2005) for baseline periods of 2000–2014 (Papers I, III–IV) and 1950–2000 (Paper II). For the former case, the native period (1950–2000) of the WorldClim data had to be adjusted (see Aalto *et al.* 2018a) using the Global Meteorological Forcing Dataset for land surface modelling (Sheffield *et al.* 2006) to match the period (2000–2014) that MAGT and ALT observations were representative of.

The climatic sensitivity of permafrost was assessed by estimating the influence of changing climatic parameters on the model outputs (i.e. the predicted MAGT and ALT, permafrost landform distributions, and spatio-temporal patterns in projected geohazards) (Fig. 4). Future climates were based on climate and Earth system models from the Coupled Model Intercomparison Project (CMIP5, Taylor *et al.* 2012). Different trajectories of human-induced climate change were taken into account using the *representative concentration pathways* (RCPs, van Vuuren *et al.* 2011). RCPs represent the estimated radiative forcing values by 2100 based on human-induced greenhouse gas emissions; according to the most optimistic (RCP2.6) pathway, emissions peak in the 2020s while the 'business-as-usual' pathway (RCP8.5) assumes a constant increase (van Vuuren *et al.* 2011). In this thesis, two future periods were considered; mid-century (2041–2060) and late-century (2061–2080). To address a broad spectrum of model responses and associated uncertainty (Thuiller *et al.* 2019), multiple emission trajectories, namely RCP2.6, RCP4.5 and RCP8.5, were included in the assessment of permafrost degradation-related hazards to the infrastructure (Papers III–IV). In the exploration of the climate change effects on permafrost landforms (Paper II), RCP4.5 and RCP8.5 were considered.

4.2.2 Terrain properties

Digital elevation models (DEMs) were the first-order source for topographical predictors. As discussed in section 2.1.3, the topography regulates the local air temperature and soil moisture conditions, for example (Etzelmüller *et al.* 2001). It is important to note, that the model fit and predictive performance are influenced by the resolution of the geospatial data layers (Yates *et al.* 2018). DEM-derived predictors at a 30 arc-second resolution (~1 km^2) were here assumed to represent terrain properties on scales which are relevant to the local variability of the studied responses on a circumpolar scale. Notwithstanding, finer-scale variations in micro-climatic, soil and hydrological conditions especially in heterogeneous topographies undoubtedly exist (e.g. Hoelzle *et al.* 2001; Etzelmüller 2013; Fiddes *et al.* 2015; Aalto *et al.* 2018b).

Solar radiation input was computed using the parameterization by McCune & Keon (2002). Based on a DEM-derived slope, latitude and aspect, the method yielded an annual estimate of the potential incident solar radiation (PISR, MJ cm^{-2} y^{-1}). The slope gradient, computed using the ArcGIS Spatial Analyst extension, was used as an independent factor in geohazard formulation and in Paper II. The topographical wetness index (TWI), used in Paper II, was computed in SAGA GIS with the SAGA Wetness Index tool (Böhner *et al.* 2002). In addition to the slope, it involved a computation of the specific catchment area (Böhner & Selige 2006). The index represents the accumulation potential of water in a grid cell based on its position in the catchment area.

Soil properties were derived from data layers in the SoilGrids database (Hengl *et al.* 2014, 2017). The contents of soil organic carbon (SOC, g kg^{-1}), coarse sediments (coarse fragments > 2 mm, %) and fine sediments (sum of clay and silt, ≤ 50 μm, %) were averaged over seven depth intervals from the ground surface to a depth of 200 cm. In Papers III and IV, SOC data provided for the depth of 60–100 cm was used. The geohazard index parameters in Paper III involved an estimation of soil and sediment thickness, for which the gridded data by Pelletier *et al.* (2016) was used. The classic "Circum-Arctic Map of Permafrost and Ground Ice Conditions" by Brown *et al.* (2002) provides the only currently available circumpolar spatial data on the ground ice content. The classified volumetric ground ice content zonation in this data was used in geohazard formulation. The potential contribution of water bodies to ground thermal regimes was taken into account in Papers II–IV using remote sensing data (Defourny 2016). Finally, the effects of vegetation cover on the MAGT and ALT were assessed by computing a normalized difference vegetation index (NDVI, Didan 2015) averaged over summer months (June to August) for the 2000–2014 period using the Moderate Resolution Imaging Spectroradiometer (MODIS) data.

4.2.3 Infrastructure data

Prior circumpolar assessments of permafrost degradation-related geohazards have not explicitly determined the amount of infrastructure at risk. This is due partly to their coarse spatial resolution but also to the lack of available globally coherent data on infrastructure elements. In Paper IV, sub-square-kilometre spatial resolution of mapped geohazards required spatially accurate data on the studied infrastructure, which was compiled from available databases (Table 1). The included infrastructure elements were chosen based on their relevancy to the human and industrial utilization of the permafrost regions. Linear features consisted of transportation infrastructure; roads, railways and pipelines, whereas airports and populated settlements were included as point locations, and buildings, industrial areas and hydrocarbon extraction areas as polygon footprints. Most of the data were derived from the national excerpts of OpenStreetMap database (OpenStreetMap contributors 2016) acquired from geofabrik.de. Some of the included features were reclassified in order to reduce the risk of data quality discrepancies across the study area. For example, only the five most important types of roads were included in order to alleviate the spatially imbalanced data completeness, i.e. developed countries and urban areas have a higher mapping density than less developed and rural areas (Barrington-Leigh & Millard-Ball 2017). In addition, raster data on census-based human population for the year 2015 (Center for International Earth Science Information Network 2016) was used to characterize the human distribution across the permafrost domain.

4.3 Statistical modelling

In statistical modelling, responses (here MAGT, ALT and permafrost landform presence/absence) are related to predictors (environmental conditions represented by geospatial data) through correlative relationships (e.g. Guisan & Zimmermann 2000; Hoelzle *et al.* 2001; Yates *et al.* 2018). More precisely, the models are calibrated by fitting a function (here using regression or machine-learning algorithms) between field observation and the values for multiple predictors at the corresponding location. In this thesis, multivariate statistical models were implemented both to explain complex process-environment relationships and thereby provide insights into the functioning of Earth surface systems on a circumpolar scale, and to predict permafrost parameters in space and time.

Based on the explorative analyses, moderately strong ($> r\ |0.7|$) bivariate correlations potentially introducing a multicollinearity effect (Dormann *et al.* 2013) occurred between certain predictors in a few modelling datasets, e.g. between air temperature and solar radiation (Fig. 2 in Paper I), rainfall and TDD, and TWI and slope (Supplementary Figure 3 in Paper II). Omitting physically relevant predictors with distinct hypothesised effects on the responses, however, was not desirable. Notwithstanding, the possible effects of multicollinearity had to be carefully considered in interpretations of the results (Dormann *et al.* 2013).

Earth surface systems and geomorphic processes often have a nonlinear nature, i.e. the outputs of a system are not proportional to the inputs across their entire range (Phillips 2006). Nonlinearities can be examined with response curves, which can yield insights into the often-complex process-environment relationships and facilitate theoretical discussions (Hjort & Luoto 2011). Visualizing the responses also brings transparency to the model evaluation and interpretation (Elith *et al.* 2005) by allowing assessments of realism between the found correlative relationships (Austin *et al.* 2006). Here, response curves were used to assess the shape and direction of the responses of MAGT and ALT (Paper I) and permafrost landforms (Paper II) to environmental predictors. In addition, Paper I included an analysis of the effect size that could be used to assess the magnitude of each predictor in the units of the response (°C for MAGT, cm for ALT). To allow further insights, Papers I and II included analyses of variable importance (Breiman 2001). In this procedure, the correlation (Pearson's r) is computed between a model fitted with all the environmental predictors and another model where one predictor is randomized. The procedure is repeated to randomize each predictor in turn. The higher the variable importance score, the higher individual contribution a predictor has to a response (Thuiller *et al.* 2009). Predictive distribution modelling was a central part of Papers II–IV. Statistical *ensemble* forecasting of MAGT and ALT (Papers III–IV) was applied to derive the current permafrost extent (2000–2014, modelled MAGT ≤ 0 °C) and ALT distribution, and to assess corresponding changes in future conditions (2041–2060 and 2061–2080) under climate-change scenarios (Section 4.2.1). In paper II, the current and future distributions of the studied permafrost landforms were predicted using a similar approach.

All the analyses in this thesis were performed using four statistical modelling techniques (see Papers I–IV and Aalto *et al.* 2017, 2018a for details). *Generalized linear models* (GLMs, Nelder & Wedderburn 1972) and *generalized additive models* (GAMs, Hastie & Tibshirani 1986) have been frequently applied in predictive spatial modelling contexts (*statistical distribution modelling*) (Guisan *et al.* 2002). Multivariate statistical modelling in geomorphological research began to emerge in the late 20th century (see Luoto & Hjort 2005). More recently, machine learning-based methods have gained ground in the fields of distribution modelling (Luoto & Hjort 2005; Hao *et al.* 2019). Here a *generalized boosting method* (GBM, Elith *et al.* 2008) and *random forest* (RF, Breiman 2001) algorithms employing machine-learning were used. The final ALT modelling in Papers III–IV was based only on GLM.

The multi-model approach comes with both advantages and challenges. The inclusion of machine learning to accompany conventional statistical methods brings efficient alternatives for model selection, tuning and evaluation (Elith *et al.* 2008; Marmion *et al.* 2008). For example, GBM allows for building models that iteratively concentrate on improving the predictions of initially weakly explained cases across the dataspace, thereby reducing bias and variance (Friedman *et al.* 2000). Additionally, in contrast to GLM and GAM, machine learning methods can automatically select relevant predictors and identify and model interactions among them (Friedman *et al.* 2000; Elith *et al.* 2005, 2008; Thuiller *et al.* 2009). GLM and GAM are additive methods, and here they were applied by simply summing up the contributions of the model terms (fitted predictors), without taking into account the interactions among them (Elith *et al.* 2005). Hence, owing to the different abilities of the models to handle aspects including collinearity, spatial autocorrelation or nonlinearity, the models may perform differently with the used environmental data (Marmion *et al.* 2009; Zhu & Peterson 2017).

The main reasons for employing ensemble and model-averaging techniques were to account for inter-model variability and reduce the uncertainty involved in choosing a single modelling method (Araújo & New 2007, Marmion *et al.* 2009; Thuiller *et al.* 2009). These techniques help reduce uncertainty by smoothing out extreme outcomes from different methods, but also from any single modelling method that can yield spurious results due to the stochasticity involved in iterative data sampling and predictor selection. Furthermore, a multi-modelling approach can be used to address uncertainty based on the agreement between model predictions (Araújo & New 2007; Luoto *et al.* 2010). Accounting for the possible variability in model predictions is especially relevant when making climate change assessments (Araújo *et al.* 2019). Obviously, ensemble model results are still dependent on the performance of the individual methods (Marmion *et al.* 2009).

4.3.1 Geohazard assessments

The estimation of potential geohazards related to near-surface permafrost degradation comprised of two main parts. First, results from the statistical modelling of MAGT and ALT were used to derive the current (2000–2014) and future (2041–2060 and 2061–2080) permafrost extents and ALT distribution. Next, geohazard indices were formulated by incorporating geospatial data (Table 1) on factors affecting the susceptibility of permafrost ground to hazardous developments, i.e. permafrost degradation and subsequent thaw subsidence, loss of bearing capacity or slope instabilities (Osterkamp & Romanovsky 1999; Streletskiy & Shiklomanov 2016; Romanovsky *et al.* 2017; Beniston *et al.* 2018; Streletskiy *et al.* 2019). The included indices were the settlement index (I_s) formulated after Nelson *et al.* (2001, 2002), the risk zonation index (I_r, Daanen *et al.* 2011) and an analytical hierarchy process-based index (I_a) formulated for this study using the framework by Saaty (1980). Finally, based on the three indices a consensus index (I_c) was computed using a majority vote, in which two out of three indices had to agree on the hazard potential (low, moderate or high) to assign a respective value for I_c.

The quantification of the amount of infrastructure at risk was based on I_c and was executed using spatial tools in the ArcGIS environment (ESRI 2015). For each scenario used, the infrastructure and population data (Table 1) were overlain on geohazard maps and the length, area or number of engineering elements intersecting the geohazard areas were summarized. To estimate the lower and higher uncertainty limit of the projections, the procedure was repeated for separate indices using MAGT and ALT predictions based on the predetermined 95% prediction intervals (see Section 4.3.2).

4.3.2 Model evaluation

Validating forecasted model results (e.g. landform distributions) in a different time or place is often not applicable due to the lack of available validation data (Hao *et al.* 2019). In this thesis, no independent validation data were compiled, but the model performance was assessed with cross-validated calibration data using statistical evaluation metrics. In a *k*-fold cross-validation procedure, all the available data was input into the model and randomly split into calibration (here 70%) and evaluation datasets (30%) (Aalto *et al.* 2017). The procedure was repeated 100 times to address the stochasticity involved in single random samples, and finally the produced evaluation metrics were averaged. In Papers III and IV, the potential effect of spatial autocorrelation (underestimated prediction error) on the model outputs was mitigated by using a distance-based evaluation (Roberts *et al.* 2017). Therein, observations in the evaluation dataset were selected at each round so that they were located farther than the predefined distance of the significant spatial autocorrelation from the calibration data used in the same round (Roberts *et al.* 2017).

Based on cross validation, the coefficient of determination R^2 adjusted by the sample size of each dataset was determined (Papers I–IV) to assess the amount of explained variation in the modelling datasets. In Paper I, the prediction error in °C for MAGT and cm for ALT were reported with root-mean-square errors (RMSE). In Paper II, predicted classifications (presence/absence) were evaluated by the area under the receiver-operating characteristic curve (AUC, Hanley & McNeil 1982) and the true skill statistic (TSS, Allouche *et al.* 2006). Finally, Papers III and IV involved a comprehensive uncertainty assessment based on a resampling procedure, wherein 95% prediction intervals were computed for 100,000 randomly chosen grid cells across the study area over 1,000 predictions (see Aalto *et al.* 2018a).

5 Results and discussion

In this chapter, I discuss the main outcomes of the four papers in answer to the research questions (Fig. 5, RQ 1–5, see Section 1) and lastly assess the contribution of the performed research to permafrost science. First, new insights into the circumpolar controls of MAGT and ALT are discussed based on the outcomes of Paper I. Next, the projected changes in the potential environmental spaces of occurrence for pingos, ice-wedge polygons and rock glaciers in a changing climate (Paper II) are assessed based on the examinations of their circumpolar controlling factors.

The concept of climate change and associated permafrost degradation are further addressed in more applied research presented in Papers III and IV. The produced circumpolar geohazard indices and projected permafrost extents for the 21st century are presented first, followed by discussions of the mechanisms behind near-surface permafrost degradation-related geohazards. Next, the new information on changing permafrost conditions produced in this thesis is synthesized to quantify the amount of Arctic infrastructure in the areas of the projected geohazards (Paper IV). In this context, the natural and societal consequences of the changing permafrost regimes will be briefly discussed. Finally, methodological issues are considered, and the performed research is placed into a larger context.

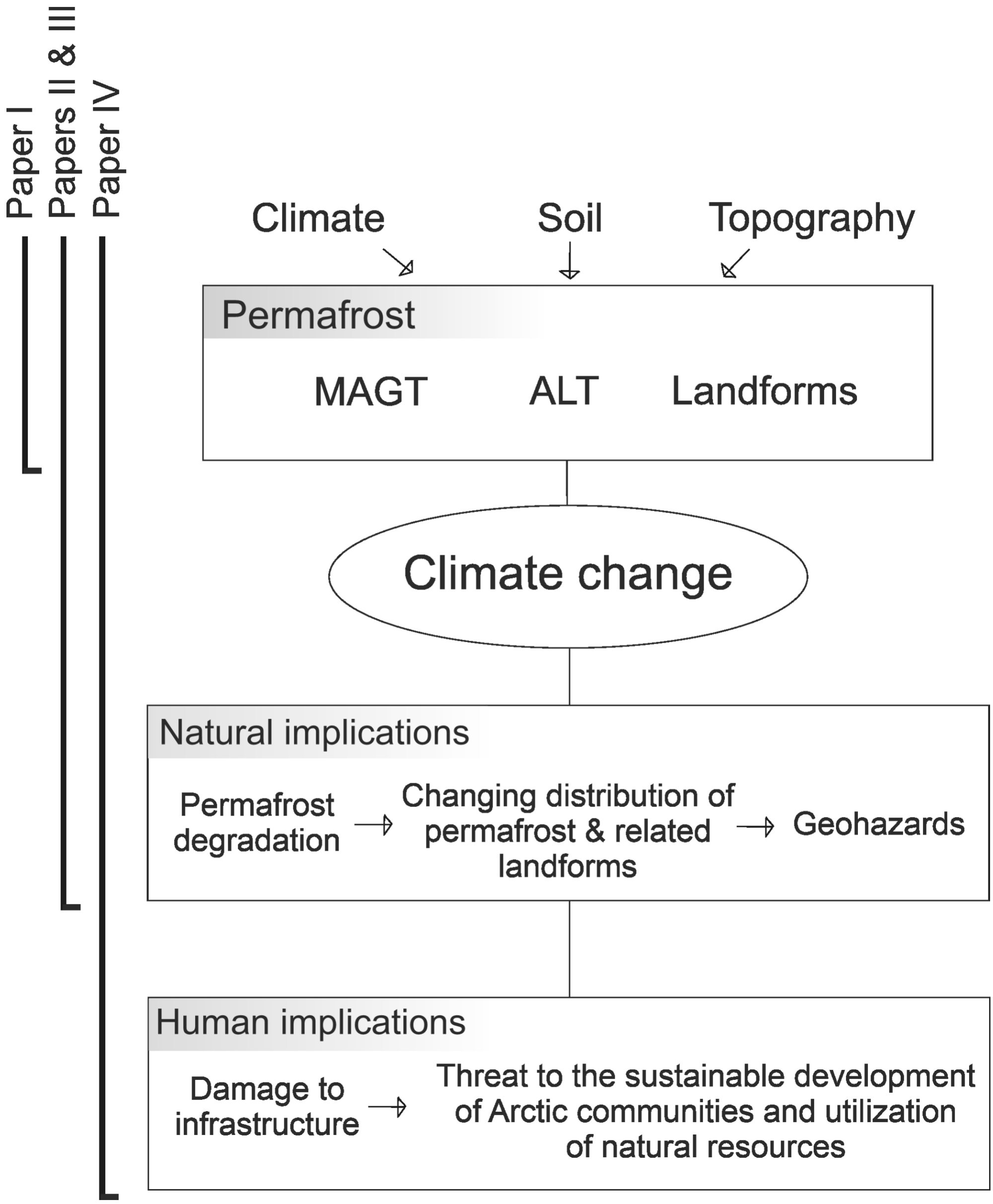


Figure 5. A thematic overview of the thesis and associated research papers. The brackets denote the overarching themes covered by individual papers. The abbreviated permafrost characteristics are the mean annual ground temperature (MAGT) and active-layer thickness (ALT).

5.1 Circumpolar controls of permafrost (RQ 1)

The overarching message of Paper I was that on a circumpolar scale climatic conditions dominate the spatial variation in MAGT and ALT, and that local conditions have a relatively small mediating effect. New insights were provided in the detailed examinations of the relative importance of the environmental controls (Fig. 3 in Paper I) and the magnitudes of their effects (Table 2 in Paper I). Importantly, response curves (Fig. 4 in Paper I) were used to identify thresholds at which the system behavior (relationship between MAGT or ALT and an environmental predictor) changes, i.e. the points at which nonlinearities in the responses occur (Phillips 2006; Hjort & Luoto 2011). These findings helped to explain the pronounced nonlinearity in the effects that climatic changes, for example, may have on the ground thermal regime.

Paper I illustrated how the presence of permafrost affects the relative importance of environmental factors on a circumpolar scale. While the freezing-season air temperature was most important factor for permafrost temperatures, in non-permafrost conditions (MAGT > 0 °C) ground temperatures were overwhelmingly controlled by the thawing season air temperature and the importance of precipitation was smaller than in permafrost conditions. Moreover, a strong nonlinearity between MAGT and FDD (a weakened response when MAGT was close to 0 °C) was found in permafrost conditions. These findings suggest that the latent heat effect associated with the ice content in the ground (e.g. Riseborough 1990; Romanovsky *et al.* 2010) applies on a hemispheric scale. Further discrimination, e.g. of continuous and discontinuous permafrost regions would help to assess the magnitude of the effect's spatial variation inside the permafrost domain.

Modest effects of soil properties on the MAGT, especially SOC, were to a degree incongruent with previous research that has emphasized their roles on the site scale (Westermann *et al.* 2010; Atchley *et al.* 2016; Nicolsky & Romanovsky 2018; Rasmussen *et al.* 2018). Here, the discrepancies were suggested to be attributed to the greater global variation in the climatic factors which was interpreted to have suppressed the effects of local factors. This assumption is in line with the pronounced scale-dependency encountered in geomorphic distribution modelling (e.g. Hoelzle *et al.* 2001; Hjort *et al.* 2010; Gangodagamage *et al.* 2014; Mishra & Riley 2014). Moreover, the limited ability of the used data (Hengl *et al.* 2017) to resolve fine-scale variation in soil properties on the site scale may partly explain their relatively small effects. In addition, the SOC predictor depicts organic carbon in fine earth fraction and can thus be seen as a proxy for the amount organic matter in the soil, which could more explicitly address the temperature offset between the ground surface and permafrost.

Permafrost landform occurrences were also strongly dependent on climatic factors (Fig. 3 in Paper II). In the cases of pingos and ice-wedge polygons, rainfall manifested as a key control on a circumpolar scale. In addition, soil moisture conditions (as depicted by topographical wetness index, TWI) and proportion of coarse sediments were central for their occurrence (Fig. 3 in Paper II). It should be noted, that although rainfall's effect on pingos and ice-wedge polygons was supported by both the analysis of variable importance and the uniform response curves for each modelling method, its effective contribution on finer scales is highly complex and realized through soil moisture feedback mechanisms (e.g. Zhang *et al.* 2001). Rock glaciers were primarily controlled by air temperatures, yet the importance of TWI and coarse sediments was at a similar level to that of FDD and TDD. Congruent rock glacier mechanics have been documented on regional scales (Marcer *et al.* 2017), but also factors that here were of smaller importance (solar radiation and precipitation) have been stressed (e.g. Hoelzle *et al.* 2001; Boeckli *et al.* 2012; Lilleøren *et al.* 2013; Ran & Liu 2018). However, the effect of precipitation in the above studies appears to be variable, and in many cases only snowfall is discussed.

Solar radiation showed variable effects on the ground thermal regime and permafrost landforms. The dominant effect of PISR on ALT on a circumpolar scale was suggested to be partly due to a poleward decrease in solar radiation that the ALT sites often situated in flat terrains without local topographical shading strongly reflected. For this reason, PISR was not included in the analyses of pingos and ice-wedge polygons, which also predominantly occur on gentle topography. A moderate warming effect of solar radiation was demonstrated for MAGT that is often monitored in topographically more variable environments (Table 2 and Fig. 4 in Paper I). Increasing PISR was also found to reduce the suitability of environmental conditions for rock glacier occurrence yet the effect was weak (Fig. 3 and Supplementary Figure 2 in Paper II).

In Paper I, GBM and RF were less stable overall than GLM and GAM when comparing the R^2 and RMSE values between the calibration and evaluation datasets, i.e. they might have shown some overfitting in the model calibration. Similar findings were reported by Marmion *et al.* (2008) in a periglacial landform distribution modelling context. Elith *et al.* (2008) argued that appropriately controlled (with pre-defined modelling parameters) overfitting in boosting methods does not compromise predictions made with new data. With GBM and RF, the possibility of overfitting was controlled by using relatively few predictors (9 to 11 depending on the response) and by using a slow learning rate, i.e. to ensure that individual trees would not have an overly large contribution to the final model (Elith *et al.* 2008).

In Paper II, GBM and RF models had higher R^2 values than GLM and GAM and fitted well to the response data. This is suggested to be visible in the response curves, which were able to identify realistic thresholds between landform occurrence and environmental factors (Fig. 3 in Paper II). For example, GBM and RF indicated a decline in the rock glacier occurrence probability when FDD approached zero, but smoother curves for GLM and GAM indicated that this effect was not captured. For this reason, the predicted rock glacier distributions from GLM and GAM were considered to be too wide. Notwithstanding, the response curves for most predictors were uniform among the modelling methods. The ability of GBM and RF to handle sharp discontinuities in the relationship was an important property, especially because the modelled landforms occupied only a small part of the sampled environmental space (see Elith *et al.* 2008). Using field-verified evaluation data on periglacial landforms from multiple high-latitude regions, Hjort *et al.* (2014) concluded that machine-learning-based methods slightly over-performed GLM and GAM when distribution models were transferred to different regions.

Based on the analyses of variable importance from Papers I and II, it can be concluded that climatic factors have a central but not uniform control over permafrost characteristics. The results of the two papers can be synthesized given that the variable importance procedure is independent of the used modelling techniques (Thuiller *et al.* 2009). Figure 6 portrays the importance of climatic predictors (other predictors are not considered for clarity) based on their mutual order of importance for each response. Not a single predictor is unanimously prevalent for all the responses, although rainfall is first in importance (thickest line) for ALT, pingos and ice-wedge polygons. These results suggest that top layers of permafrost are particularly dependent on rainfall-induced soil moisture and associated alterations in heat fluxes.

It should be noted that rainfall was moderately correlated with TDD in the pingo and ice-wedge polygon datasets (Spearman's rank correlation $r_s = 0.63$ and 0.81, respectively), and thus possibly contained the same information. For MAGT and rock glaciers, FDD showed the most importance and rainfall was less relevant (yet still third in importance across all predictors, see Paper I). The modest contribution of snowfall for most responses was surprising, given its pronounced role in buffering the ground thermal regime from atmospheric conditions (e.g. Zhang 2005). This may have been because the used climate-data derived snowfall predictor has a limited ability to depict the fine-scale spatial variation in snow depth, which is ultimately driven by topography and azonal processes, such as wind (French 2007). Still, the shape of the response (Fig. 4 in Paper I) indicated a warming effect of increasing snowfall for MAGT in permafrost conditions.

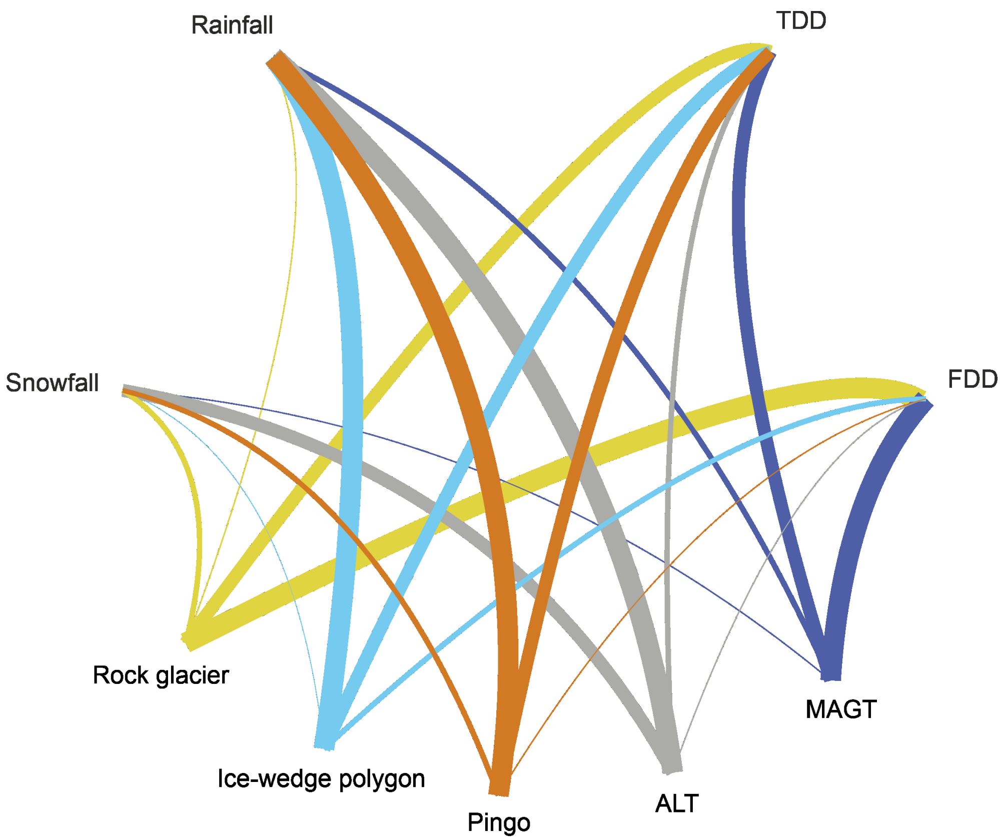


Figure 6. A synthesis of climatic controls for the studied thermal and geomorphic permafrost characteristics. The climatic controls of the mean annual ground temperature in permafrost conditions (MAGT ≤0 °C), active-layer thickness (ALT), pingos, ice-wedge polygon and rock glaciers are presented based on a variable importance analysis. The line widths depict the relative importance of a climate predictor, with the thickest being the most important for the respective response. Abbreviated predictors are freezing- (FDD) and thawing-degree days (TDD).

5.2 Permafrost in changing climates (RQ 2)

5.2.1 Permafrost extent and active-layer thickness dynamics

Based on the baseline (2000–2014) ensemble prediction estimate, permafrost (i.e. modelled MAGT ≤ 0°C) covered around 15.1 × 10^6 km^2 of the Northern Hemisphere (Table 3 in Paper III). Considering the determined 95% prediction intervals, the area ranged between 13.0 and 17.2 × 10^6 km^2. The baseline ALT predictions had a relatively high uncertainty range of ± 37 cm. Model performances were evaluated internally with repeated random cross validation and externally against observational data from the assigned past periods (1970–1984 and 1985–1999). Evaluations showed that the modelling could well explain the MAGT variability in the baseline, but also in past periods, which indicated a reasonable degree of model transferability. ALT modelling had lower evaluation statistics and was able to detect much more generalized trends. However, in both cases uncertainty did not increase when modelling past periods (Table 3 in Paper III).

The baseline permafrost extent was generally congruent with the previous (Dankers *et al.* 2011; McGuire *et al.* 2016; Chadburn *et al.* 2017; Guo & Wang 2016, 2017b) and subsequent (Obu *et al.* 2019) models in terms of the total areal coverages and regional patterns. Direct comparisons, however, were limited by the different means of delineating the permafrost existence; some studies relied on soil temperature, others on ALT, and in some cases also the thickness of the soil horizons or permafrost zones considered to constitute permafrost domain differed. Importantly, the modelling results in Paper III did not imply that all the permafrost would degrade where thawing is predicted, but rather those areas would no longer be sustainable for near-surface permafrost.

Future simulations in Paper III using a medium climate-change stabilization scenario (RCP4.5) suggested that near-surface permafrost would disappear from extensive areas by the mid-century (Fig. 7a). The largest areal losses were associated with low-lying areas at the southern front of the circumpolar permafrost domain, especially in north-western and central Siberia (Fig. 7a). Late-century projections indicated continued shrinking dependent on human-induced greenhouse gas trajectories. For example, attaining the RCP4.5 trajectory (i.e. emissions are assumed to peak around 2040 and then decline) could yield ~27% smaller losses of near-surface permafrost than the 'business-as-usual' RCP8.5 trajectory by 2061–2080 (Table 3 in Paper III).

In addition to the near-surface permafrost thaw over large areas, an increase in the ALT was projected to occur extensively across cold high-Arctic areas (Fig. 7b–d). Although the air temperature drives the ALT on broad scales and over longer time periods (e.g. Bonnaventure & Lamoureux 2013), regional ALT trends have expressed more complicated responses to climatic forcing due to aspects such as the combined effects of snow depth and soil moisture (Park *et al.* 2013; Luo *et al.* 2016). Koven *et al.* (2013) attributed the ALT-air temperature anomaly to soil conditions and fine-scale hydrology and argued that omitting them from the analysis would attribute too much of the ALT variance to the climate. In Paper I, soil properties (SOC and coarse sediment content) and snowfall made larger individual contributions than TDD or FDD (Table 2 and Fig. 3 in Paper I), which promotes this view, although it should be born in mind that therein the focus was on the spatial controls of ALT rather than its temporal development. Moreover, the used soil (Hengl *et al.* 2017) or climate (Hijmans *et al.* 2005) data could not fully represent the soil and microclimatic conditions on a fine scale that ALT is known to vary spatially (Hinkel & Nelson 2003).

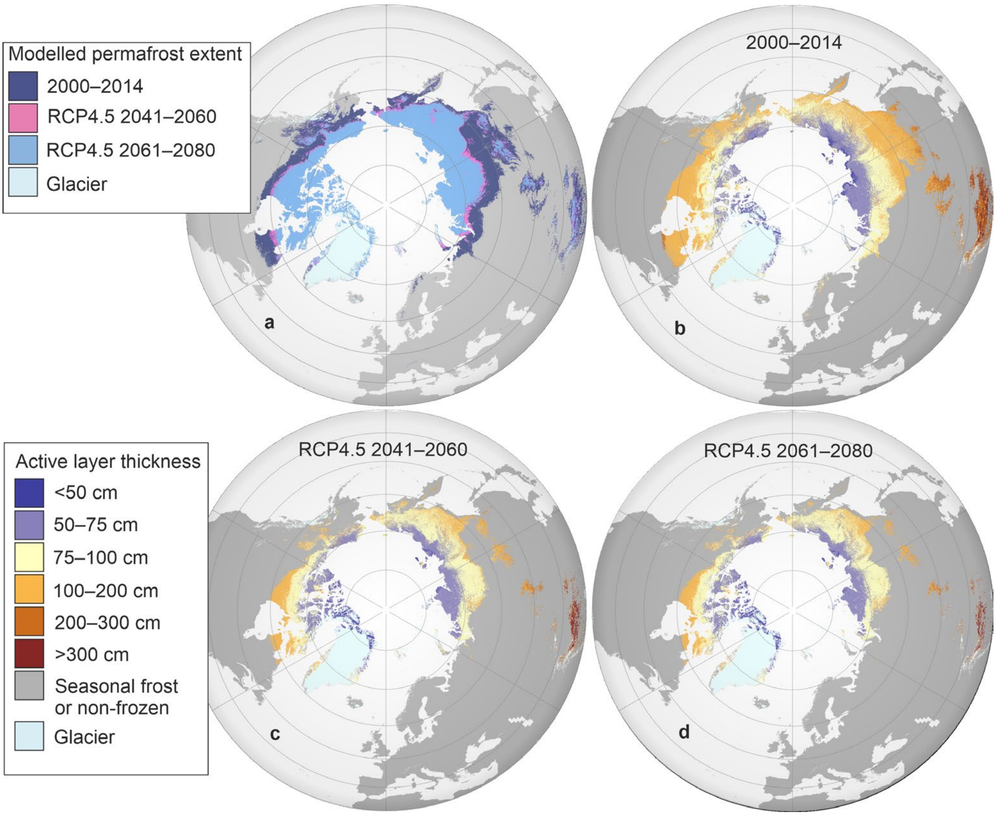


Figure 7. The modelled permafrost extent in current conditions (2000–2014) and in 2041–2060 and 2061–2080 based on a representative concentration pathway (RCP4.5) climate-change scenario (a). Predictions of the active-layer thickness for the corresponding scenarios are presented in panels b–d.

5.2.2 Potential environmental spaces for permafrost landform occurrence

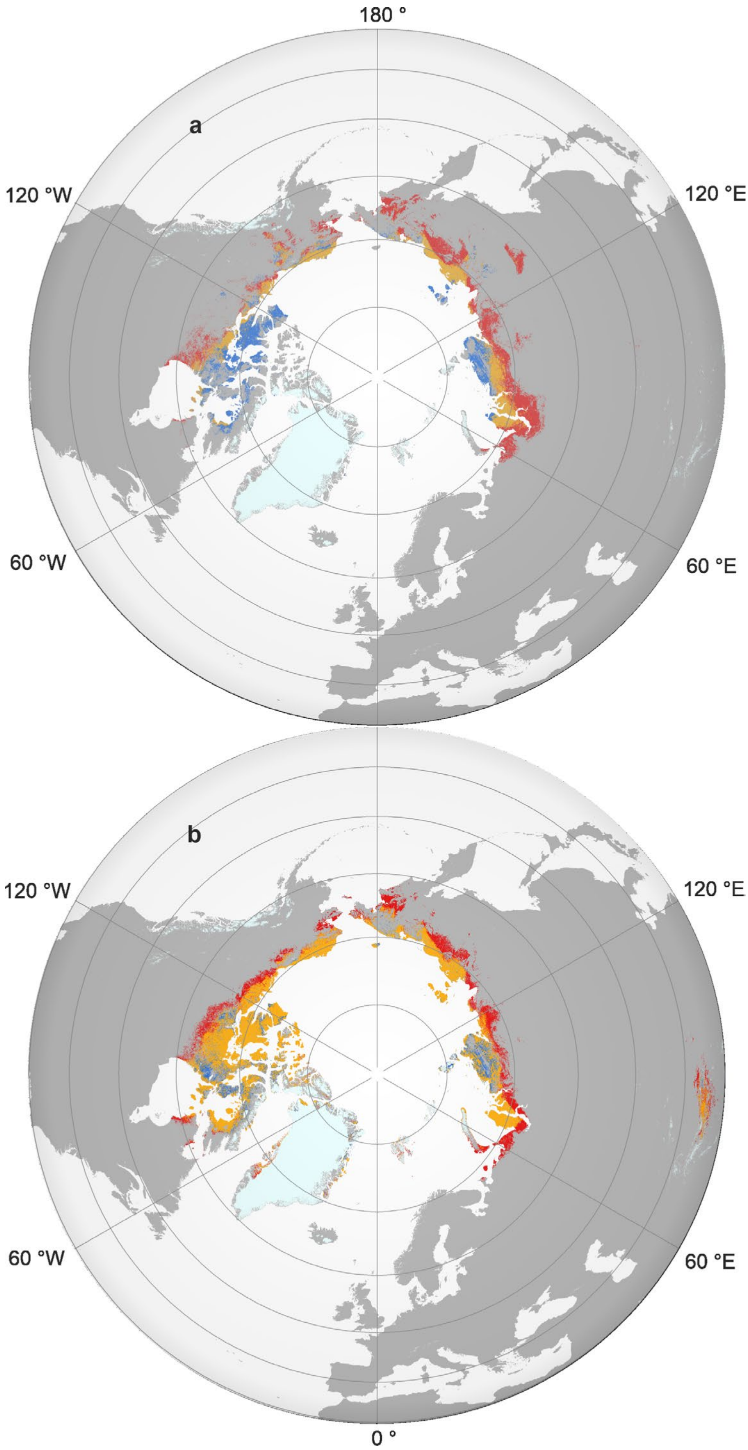
The ensemble forecasting of permafrost landforms revealed considerable changes in their potential distributions by the mid- and late-century. For the considered climate-change scenarios, environmental spaces reduced by 21–29% between the baseline period (1950–2000) and 2041–2060 (RCP4.5), and by 30–40% when compared to 2061–2080, depending on the landform (Fig. 8). Given potentially stronger radiative forcing (RCP8.5), corresponding reductions were 30–41% and 46–67%. The largest areal changes in all cases were forecasted for pingos, while ice-wedge polygons and rock glaciers faced slightly smaller losses (Fig. 8d). Interestingly, the projected losses were not confined to the modelled areas of thawing near-surface permafrost (Fig. 7) but occurred abundantly in cold continuous permafrost regions (Fig. 8). This may be because wedge ice, for example, forms just below the active layer and thus is highly sensitive to greater thawing occurring during warm summers (e.g. Jorgenson *et al.* 2015; Lewkowicz & Way 2019).

In cold permafrost regions, the lack of buffering vegetation and thick soil organic layers promotes the strong effect of increasing summer temperatures (Farquharson *et al.* 2019; Ward Jones *et al.* 2019).

The aggradation and degradation of ice-wedge polygons have been suggested to serve as a proxy for changes in the climate owing to their pronounced climatic dependency (Liljedahl *et al.* 2016; Farquharson *et al.* 2019). Rock glaciers, also, have been argued to be sensitive to a warming climate and can thus serve as a valuable indicator of the geo-ecological state of mountain environments (Barsch 1988; Humlum 1998). These responses are complicated by the many processes behind permafrost aggradation and degradation that are strongly affected by local hydrological, surface and ground-ice conditions (Romanovsky *et al.* 2017b), which themselves are dynamic and prone to evolve in a changing climate (Shur & Jorgenson 2007). The pronounced nonlinearities documented in the responses of landforms in Paper II imply that they had different sensitivities to climatic changes. Regardless of the above-mentioned intervening feedback processes, it can be argued that any landforms near a threshold point for a potential occurrence are the most sensitive (see Phillips 2006). In this regard it is suggested that the pingos and ice-wedge polygons with air temperature and rainfall values close to the minimal or maximal limit of optimal conditions, or rock glaciers close to the minimal or maximal TDD conditions, are most prone to change (Fig. 3 in Paper II). Warm rock glaciers (with ground temperatures close to 0 °C) have been indeed considered to show elevated vulnerability to climate warming (Kääb *et al.* 2007). However, Jones *et al.* (2019b) stress that the response of rock glaciers to future climate changes remains highly understudied.

It is important to note that the projected changes depict potential distributions based on the realized occurrences of the landforms in current conditions. The predicted suitable conditions for current and future occurrences delineate areas where the landforms can persist and new landforms can form, but the modelling cannot directly involve the geomorphic processes behind the degradation or formation of any individual landforms. Moreover, the decaying of a pingo, for example, can be initiated naturally without climatic forcing when its thermally protective overburden ruptures at a point of its life cycle (Gurney 1998; Mackay 1998). In certain conditions where ecosystem characteristics protect permafrost from warming climate (Shur & Jorgenson 2007), landform preservation is possible even if climate was predicted to be unsuitable for occurrence. Moreover, the full degradation of landforms can take notably longer than the studied time period with the possible exception of ice-wedges, which can melt for their upper parts in the matter of decades (Liljedahl *et al.* 2016).

Changing permafrost landform distributions are prone to involve system-wide consequences, e.g. with implications on hydrology, geo- and biodiversity, biogeochemical processes, and freshwater availability. Notwithstanding that new potential areas for landforms were also projected (Fig. 8), the magnitude of the areas of potential loss was high enough to argue that shifting regimes of permafrost landforms should be considered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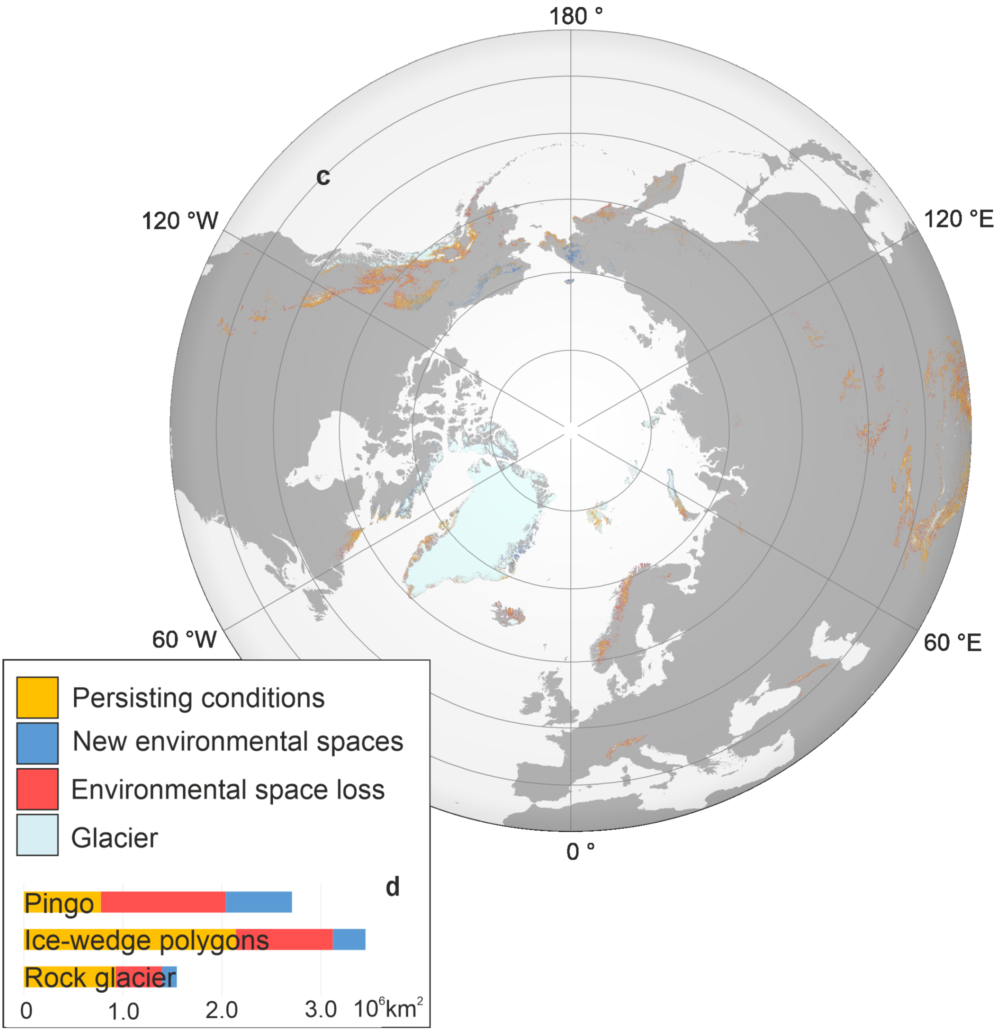

Figure 8. Projected potential environmental spaces for permafrost landforms in 2041–2060 based on a representative concentration pathway (RCP4.5) climate-change scenario. Persisting conditions as well as potential new and lost environmental spaces are depicted for pingos (a), ice-wedge polygons (b) and rock glaciers (c). Corresponding projected areal coverages are summarized in panel d.

when assessing the impacts of climate change on natural and human systems. Along the lines of Moon *et al.* (2019), it could be argued that even though permafrost-affected area is shrinking, the global impact of the changes is growing both inside and outside the Arctic.

5.3 Geohazards related to near-surface permafrost degradation (RQ 3)

The spatial patterns of the hazard potential depicted by the consensus index (I_c, Fig. 9) reflect the degradation of permafrost as demonstrated earlier by the shrinking permafrost extent (Fig. 7a) and projected environmental space losses concerning permafrost landform occurrences (Fig. 8). Importantly, substantial thawing did not necessarily translate into a severely high hazard potential but was dependent on local terrain properties. Considering the variation in regional conditions, the critical areas based on the analyses were north-western and -eastern Siberia and the Yakutsk basin in central Siberia, as well as central and western parts of Alaska (Fig. 3 in Paper IV). Of concern for the currently existing infrastructure was the finding that most of the projected high hazard potential could already be realized by 2041–2060. Notwithstanding, high-hazard areas were predicted to continue to expand towards the late-century (Fig. 3 in Paper III).

The hazard potential of near-surface permafrost degradation effectively depends on the soil properties and topography, for example; the thaw subsidence potential is highest in ice-rich soils and fine sediments, whereas a thaw in the bedrock or coarse-grained soils have more negligible effects on ground stability (e.g. Permafrost Subcommittee 1988; Daanen *et al.* 2011). The volumetric ground ice content is a central component of the geohazard potential as it determines the amount of subsidence that can occur when the ground ice melts (Grosse *et al.* 2011; Farquharson *et al.* 2019; Meredith *et al.* 2019). A possible source of uncertainty posed by the used ground ice content data (Brown *et al.* 2002) is that it does not distinguish between the relative proportions of pore and excess ice. The amount of excess ice effectively determines how much thaw settlement can occur, while pore ice melt does not contribute to changes in ground volume (Brown *et al.* 2000; Lee *et al.* 2014). In the I_a formulation (Paper IV), the most consequential factors for near-surface permafrost degradation-related damages to infrastructure were considered to be the ground temperature, ground ice content, relative increase in ALT, fine grained sediment content, and slope gradient.

The region-specific differences to previous regional (Guo & Sun 2015) and circumpolar applications of I_s (Nelson *et al.* 2001, 2002; Anisimov & Reneva 2006; Guo & Wang 2017a) stemmed from the used predictions of the change in the ALT, given that all used the same ground ice content data (Brown *et al.* 2002). Settlement index computation is inherently sensitive to exaggerating the settlement in areas with a thin active layer where minor absolute changes can yield very large proportional increases in the ALT. The other two indices giving less (I_a) or no (I_r) weight to the ALT change showed a lower geohazard potential for the coldest regions. Moreover, owing to the pronounced fine-scale spatial variability of ALT (see Section 5.2.1) its accurate prediction is particularly difficult, especially on a circumpolar scale (Riseborough *et al.* 2008; Koven *et al.* 2013; Aalto *et al.* 2018).

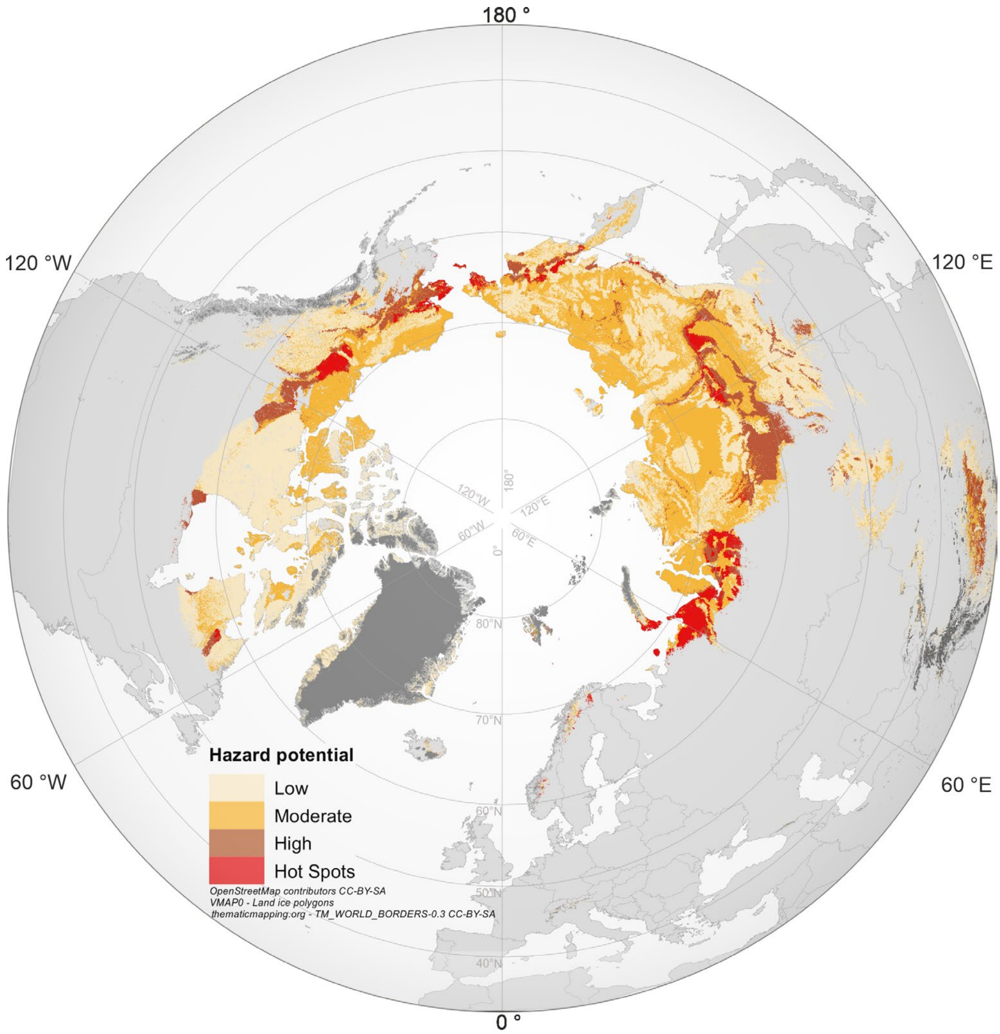

Figure 9. The permafrost degradation-related geohazard potential across the Northern Hemisphere based on a representative concentration pathway (RCP4.5) climate-change scenario for the period 2041–2060. The hot spots indicate locations for which all three computed geohazard indices (see Section 4.3.1) indicated a high hazard potential.

The published permafrost extent maps and geohazard indices (Karjalainen *et al.* 2018) have potential for reuse in future assessments of infrastructure vulnerability in changing climates as well as for targeting localized hazard assessments for regions at risk. However, the presented data-related uncertainties and the limitations posed by the equilibrium approach need to be taken into account when assessing hazard potential on a settlement scale, for example. The effective benefits for planning and engineering projects are suggested to stem ultimately from assessments employing landscape-specific local to national datasets (Riseborough *et al.* 2008).

5.4 Infrastructure at risk (RQ 4)

The main message conveyed in Paper IV is that four million people and on average 69% of engineering structures (48–87% depending on the type of infrastructure) currently in the permafrost region are situated in areas where the near-surface permafrost is predicted to thaw by the mid-century (Fig. 2 in Paper IV). Moreover, on average 33% (25–45%) of the infrastructure is located in high hazard areas which are susceptible to thaw-related ground instability and damage to infrastructure. A larger share of the infrastructure and population were found to be in areas with a high hazard potential in Eurasian land areas rather than in North America (Fig. 2 and 3 in Paper IV). Moreover, ice-rich permafrost regions, especially those close to the southern permafrost extent, were most probably at risk. These areas coincidence with a massive hydrocarbon industry and population centers in western Siberia with high levels of socio-economic activity (Badina 2017), and this is suggested to be prone to far-reaching socio-economic consequences and environmental risks.

A significant finding of Paper IV was to demonstrate how attaining the Paris Agreement goals (UNFCCC 2015) would barely affect the magnitude of the potential damage to the infrastructure by 2041–2060, but also that reduced emissions could keep notable amounts of infrastructure below the high hazard level by 2061–2080 (Supplementary Figure 4 in Paper IV). Hence, effective climate change mitigation could reduce the economic expenses (see Larsen *et al.* 2008; Melvin *et al.* 2017; Streletskiy *et al.* 2019) of permafrost degradation-related damage to infrastructure. That being said, the mitigation measures themselves are prone to impose additional economic stress on economies, particularly in Russia with relatively heavily populated and industrialized Arctic areas (Streletskiy *et al.* 2019).

Generally unpredictable socio-economic development presents a source of uncertainty that hinders the delineation of effective geohazards on fine scales. For example, the approach used did not consider adaptive engineering (e.g. technical solutions to protect the infrastructure from near-surface permafrost degradation-related instabilities) that needs to be practiced when constructing in vulnerable areas (Shiklomanov 2005; Streletskiy & Shiklomanov 2016). Neither did it take into account the expected life spans of the examined infrastructure elements, which for buildings in Russia, for example, is typically around 50 years (Streletskiy *et al.* 2012). Moreover, alongside the warming climate, the infrastructure may increase ground temperature and ALT, and accelerate deformations *per se* (Williams *et al.* 2013; Raynolds *et al.* 2014; Klene & Nelson 2019). The warming effect of the infrastructure on permafrost can be either via direct heat conduction into the ground (Daanen *et al.* 2011) or may be an indirect effect arising through the removal of the insulating organic layer (Nelson *et al.* 2002; Harris *et al.* 2009).

Already occurred damage to the Arctic infrastructure characterizes the hazards that have been suggested will become more frequent in the near future (Hong *et al.* 2014; Streletskiy & Shiklomanov 2016; Melvin *et al.* 2017; Shiklomanov *et al.* 2017). Discontinuous permafrost close to the southern limit of permafrost is assumed to be most vulnerable to effective permafrost degradation-related hazards and this is attributed to its initial near-thaw conditions (Riseborough 1990; Yang *et al.* 2010; Shiklomanov *et al.* 2017). This view was supported by the analyses, although not all fringe areas were at risk owing to non-susceptible terrain conditions (see Section 5.3, Fig. 9). In practice, it is sometimes difficult to differentiate whether and to what degree specific infrastructure damage is due to climate-driven changes in permafrost or, e.g., lack of maintenance, age or design flaws (André & Anisimov 2015; Shiklomanov *et al.* 2017). The bottom line is, however, that the intensification of human activity in permafrost areas is leading to the increased frequency and magnitude of permafrost-degradation related disturbances (Grosse *et al.* 2016; Romanovsky *et al.* 2017).

In Paper II, I suggested that the shifting regimes of permafrost landforms could pose a threat to the infrastructure. For example, slope destabilization associated with degrading rock glaciers has caused damage to constructions (Haeberli 1992; Etzelmüller & Frauenfelder 2009; Bodin *et al.* 2015; Marcer *et al.* 2017). Moreover, the development of thermokarst terrain is closely associated with degrading pingos and ice-wedge polygons, and already affects one-fifth of the permafrost region (Olefeldt *et al.* 2016). The affected area is anticipated to extend in a warming climate (Farquharson *et al.* 2019).

The improved knowledge of the spatial patterns of permafrost degradation such as the knowledge produced here is required to enable policymakers to initiate adaptation strategies (Ford & Pearce 2010; Knight & Harrison 2013). Owing to the limitations of the approach in assessing the geohazard potential on the site (e.g. individual buildings, road segments) or even local scale (populated settlements), it is suggested that the results are most appropriately applied on broader scales. In practice, this involves 1) targeting localized geohazard assessments for the recognized high-hazard areas, and 2) disseminating the new information at the international level (Karjalainen *et al.* 2019; Meredith *et al.* 2019) to inform multidisciplinary permafrost science, as well as decision-making and lower level policies.

In some regions, a considerable focus has already been set on risk assessments and adaptation measures to provide guidelines, standards and engineering solutions for infrastructure development in permafrost regions (Romanovsky *et al.* 2017). In Canada, large-scale research projects, e.g. the Arctic Development and Adaptation to Permafrost in Transition (ADAPT, Vincent *et al.* 2013) project and the ArcticNet's Integrated Regional Impact Studies (IRIS), were established to address the processes and impacts of permafrost degradation, and to ultimately assess the community-scale impacts (Romanovsky *et al.* 2017). In Russia, permafrost related problems have been identified as a matter of national security in a federal Arctic development strategy, and the city of Norilsk has developed cost-effective construction practices, and city-wide monitoring and modelling of the ground thermal regime (Shiklomanov *et al.* 2017). The permafrost-climate-infrastructure connection clearly involves multiple disciplines and actors, and thus the exchange of knowledge is vital (Vincent *et al.* 2017).

5.5 Methodological considerations (RQ 5)

Exhaustive evaluations of the performed modelling indicated that a statistical approach can produce generally accurate predictions of current permafrost characteristics (Table 1 in Paper I, Supplementary Figure 1 in Paper II, Table 3 in Paper III,), although depicting the fine-scale ALT variability remained challenging. Moreover, the models could be reasonably transferred to the examined past periods according to the evaluations done with independent observation data. When discussing the applicability of the implemented methodology in the current and future modelling contexts, it is crucial to carefully consider the advantages and the inherent limitations to statistical modelling.

Potential contributions of this thesis to broad-scale permafrost modelling can be assessed by discussing how data synthesis and statistical modelling could yield new solutions alongside previously implemented methodologies. Among them, widely used process-based models (e.g. Zhang *et al.* 2003, 2005, 2018; Lawrence & Slater 2005; Lawrence *et al.* 2012; Slater & Lawrence 2013; McGuire *et al.* 2016) employ empirically established descriptions of mechanisms and parameters on the permafrost-climate relationship (Yates *et al.* 2018). Explicit parameterizations of solar radiation, heat conduction, surface albedo and sensible heat, for example, make the models realistic, in principle, but very laborious to assemble and often coarse in their spatial resolution. One of the main advantages of the statistical approach is that increasingly available observational and geospatial data can be integrated into a cost-efficient modelling framework which is able to produce high-resolution analyses on broad scales. This implies that statistical analyses are highly dependent on the available data and its quality (see Paper III, Anisimov *et al.* 2007; Marmion *et al.* 2009; Bartsch *et al.* 2016). In the context of predictive modelling, the statistical approach is often limited to using data on current soil properties or vegetation, for example, as spatial projections of other than climatic parameters are usually not attainable. Moreover, despite the wide application of statistical distribution modelling, there is no consensus regarding which algorithms are best suited for a given purpose (Araújo *et al.* 2019; Thuiller *et al.* 2019). Thus, the sufficiency of the utilized data and associated methods need to be carefully assessed when constructing statistical modelling frameworks and the results need to be rigorously evaluated (Luoto *et al.* 2010).

An inherent source of uncertainty in broad-scale permafrost studies is that the regions are remote, and thus often sparsely field sampled. While the transferability of statistical models offers a cost-effective way to assess conditions in different spaces and at different times (Hjort *et al.* 2014; Yates *et al.* 2018), modelling accuracy in unsampled regions is typically lower (Hijmans *et al.* 2005; Anisimov *et al.* 2007; Hengl *et al.* 2014, 2017). In Paper II, an analysis of spatial uncertainty revealed that the model agreement between the four used methods was indeed lower in sparsely or non-sampled regions for permafrost landforms (Supplementary Figure 8 in Paper II). Observational networks of MAGT and ALT have developed substantially especially during and after the latest International Polar Year (2007–2009) through efforts made by multinational monitoring programmes and individual research projects (Biskaborn *et al.* 2015) but several large areas are still underrepresented or completely lack data (Biskaborn *et al.* 2019). Notwithstanding, the observational network has been considered adequate to determine the general trends of permafrost change (Romanovsky *et al.* 2017).

In this thesis, extensive observational datasets of permafrost characteristics were compiled, but a geographically more comprehensive set of samples (better coverage of the entire gradient of environmental conditions) could have improved the model transferability (Yates *et al.* 2018) and reduced uncertainty (Syfert *et al.* 2013). Inarguably, field verified environmental data from, e.g., MAGT and ALT sites would be an ideal starting point for model building but standardized data is not currently available.

5.5.1 Spatial modelling in time

In Paper I, analyses examining MAGT and ALT variation across the circumpolar area using data from 2000–2014 period were strictly spatial. The other papers glanced into the future, which posed a new challenge for predictive modelling. Methods that assume the ground thermal regime to be in balance with the current climate conditions and also that the inherently dynamic ecosystem properties remain unchanged in the future are called *equilibrium* models (Riseborough 2007; Riseborough *et al.* 2008; Callaghan *et al.* 2011). The dynamics of the ground thermal regime, however, involve regulating processes such as the latent-heat exchange (see Section 2.1.2, Berggren 1943; Romanovsky *et al.* 2010; Lee *et al.* 2014) and thermal inertia of cold permafrost (Anisimov *et al.* 2007; Lawrence *et al.* 2008), which can give rise to the transient effect, i.e. a lag in permafrost thaw to the warming climate (e.g. Riseborough 2007). Furthermore, the changing hydrologic, vegetation or ground ice conditions can either accelerate or slow permafrost thaw (Shur & Jorgenson 2007; Koven *et al.* 2013).

Not implicitly addressing these processes did not, however, invalidate equilibrium approaches in the present context. First, the time lag of the response to climate signal was taken into account by using near-surface permafrost characteristics, which are of key relevance in terms of permafrost degradation-related consequences (Anisimov *et al.* 2007; Dixon 2013; Zhang *et al.* 2018a) and argued to be more readily representative of equilibrium conditions (Chadburn *et al.* 2017). Second, permafrost temperatures at DZAA reflect decadal scale air temperature changes better than interannual variations (Romanovsky *et al.* 2007). It has been shown that decadal or longer time scale permafrost temperature averages yield more accurate model predictions than those from individual years (Anisimov *et al.* 2007). Third, despite being mediated by local terrain properties and their dynamics, the magnitude of the regional climate change is suggested to exert the dominant effect on ground thermal regimes on the circumpolar scale (Nitze *et al.* 2018). Biskaborn *et al.* (2019), for example, stated that the latent heat effect in ice-rich environments cannot indefinitely delay or prevent permafrost thaw in a warming climate.

According to Lee *et al.* (2014), the presence of high excess-ice content accounts for about a 10-year delay in permafrost thaw, which in the present case is a relatively short delay.

The projected permafrost extents in Paper III were indeed comparable to previous process-based models (see Section 5.2.1) including those considering the transient effect. It should be noted, however, that the ranges in the projected permafrost extents using climate and Earth surface models from CMIP5 have been demonstrated to be extremely large (Lawrence *et al.* 2008; Koven *et al.* 2013; Slater & Lawrence 2013). Moreover, the CMIP5 general circulation models do not consider permafrost-carbon feedback, and thus many of them may underestimate the extent of global warming (Yumashev *et al.* 2019).

The above issues do not imply that involving reliable projections of ecosystem dynamics (e.g. vegetation, soil moisture, lake areas (Beniston *et al.* 2018; Nitze *et al.* 2018)) to perform transient modelling should not be pursued; in fact this constitutes a promising yet challenging future direction for refining statistically based model projections of permafrost. In this thesis, an equilibrium assumption was adopted because no suitable high-resolution circumpolar future projections on aspects such as changing ground ice, soil moisture or vegetation were available. These dynamic features markedly affect local-scale Earth surface processes and can make permafrost either more susceptible or resilient to degradation (Shur & Jorgenson 2007; Wu *et al.* 2012; Koven *et al.* 2013; Schuur *et al.* 2015). In a recent IPCC report (Hoegh-Guldberg *et al.* 2018) it was estimated that the equilibrium response of permafrost to climate change is 25–38% greater than the simulated transient response. Studying ice-wedge polygon degradation and stabilisation, Jorgenson *et al.* (2015) argued that the magnitude of ground ice dynamics and ecological feedbacks can be larger than the projected climate changes themselves, and thus greatly complicate assessments of the effects of permafrost stability.

A central factor affecting Earth surface processes and landforms for which no applicable projections were available is soil moisture. This thesis addressed this aspect indirectly by demonstrating the importance of rainfall (Fig. 6) and the topographical wetness index (Section 5.2.2) for ALT, pingos and ice-wedge polygons. These two predictors, however, are not to be likened to fine-scale soil moisture (constrained by variation in topography, soil properties and vegetation) (Kemppinen *et al.* 2018) that contributes to the thaw depth and development of ground ice on the site scale. Nicolsky and Romanovsky (2018), for example, argued that the presence of unfrozen water in the soil, especially within fine-grained sediments, can markedly slow down the long-term thawing of permafrost. Therefore, it is suggested, that more explicit inclusion of soil moisture in broad-scale statistical models would be beneficial for more reliably representing permafrost thaw (see Aalto *et al.* 2018b; Nicolsky & Romanovsky 2018).

6 Future study needs

I next discuss some possible data and methodology-related aspects that could help overcome the shortcomings identified in this thesis that limit harnessing the full potential of the statistical approach. The majority of permafrost landscapes remain understudied, which may hinder our ability to understand the actual magnitude of ongoing permafrost degradation (Nitze *et al.* 2018). Recently, more standardized and coordinated efforts to integrate data from local-scale high-resolution studies into hemispheric trends has been called for (Jorgenson & Grosse 2016). In this work, I have stressed the need for broad-scale modelling efforts to accompany the long line of local to regional studies and the possible roles of statistical modelling in doing this. The new information on the change of permafrost landscapes produced here could be further refined by incorporating ancillary methodological procedures. For example, Fick and Hijmans (2017) recently concluded that the local context strongly influenced the climate processes in their global climate surface interpolations. Therein, applying locally selected predictor groups allowed for better model fits in remote regions. Moreover, the factors behind regional climate changes have varied (Bintanja 2018), which further underlines the issue of scale. Thus, implementing knowledge from local-scale studies to more explicitly account for regional climate-permafrost dynamics as well as incorporating, for example, geographically weighted regression techniques could be a key in tackling spatial nonstationary problems and yield improvements in broad-scale permafrost modelling.

Another step towards site-scale realism when assessing the impacts of climate change on geo- and ecosystems would be to achieve a higher spatial resolution of analysis, especially in topographically heterogeneous environments (Etzelmüller 2013; Aalto *et al.* 2018b). In a regional effort, Mishra and Riley (2014) studied the ALT at a globally yet unachievable 60-m resolution in Alaska. They found that using geospatial data at a resolution consistent with the existing spatial heterogeneity of ALT yielded improvements over the standard CMIP5 Earth system model estimates. Gangodagamage *et al.* (2014) reported similar results at a 2-meter resolution. On this scale the role of eco-hydro-geomorphic factors strongly moderated broad climatic effects. A more precise temporal resolution, in turn, could help to assess the impacts of extreme climate effects on the permafrost properties, which may increase in frequency and magnitude due to climate change (Vincent *et al.* 2017). A lengthening line of studies shows that extreme summer warmth or rain events in both summer and wintertime have distinct effects on the ground thermal regime and geomorphology (e.g. Westermann *et al.* 2011; Marmy *et al.* 2013; Kokelj *et al.* 2015; Liljedahl *et al.* 2016; Zhu *et al.* 2017; Lewkowicz & Way 2019).

A key issue hindering reliable assessments of the spatio-temporal nature of permafrost degradation and the related consequences is the lack of accurate data on the current and future ground ice content. Calls for international efforts to compile and synthesize observational data have been recently proposed in high-level publications (Nitze *et al.*

2018; Schuur & Mack 2018; Turetsky *et al.* 2019). Modern solutions seek to improve the status quo circumpolar ground ice content data (Brown *et al.* 2002), and alongside local field-based studies broad-scale regional mapping products are beginning to emerge. O'Neill *et al.* (2019), for example, presented a Canada-wide assessment of ground ice type distributions. Statistical modelling has the potential to improve the understanding of fine-scale ground ice distribution on a circumpolar scale.

During the last few years, the rapid development and availability of remote sensing data and increased computational capacity have yielded a swathe of literature presenting novel, high-resolution, remote sensing applications (Grosse *et al.* 2016; Du *et al.* 2019). One of the newest and expanding fields are deep learning methods in automated mapping of permafrost landforms from very high-resolution (sub-meter) remote sensing imagery (e.g. Zhang *et al.* 2018b; Abolt *et al.* 2019; Huang *et al.* 2019). Despite the advances, monitoring the rapid changes across cold regions will need spatio-temporally more accurate data and developments in data synthesis (Du *et al.* 2019). Echoing the methodological base of this thesis, it is concluded that the future of permafrost research will be increasingly data dependent.

7 Conclusions

In this thesis, the current and future characteristics of the Northern Hemisphere permafrost were studied using a statistical modelling approach at a high spatial resolution. The main goals were to improve the understanding of the current state of the circumpolar permafrost and to assess the natural and societal implications of changing thermal and geomorphic permafrost conditions due to climate change. Below the main outcomes of the thesis are concluded against the preassigned research questions.

1. Based on the statistical analyses, climatic conditions are the main controls of circumpolar permafrost. ALT, pingos and ice-wedge polygons showed strong sensitivities to the amount of rainfall and the air temperature. MAGT and rock glaciers were the most responsive to the air temperature. The effects of local soil and topography properties, however, had non-negligible roles in defining finer-scale variation especially for ALT and rock glaciers. In addition, the analyses provided new insights into how the nonlinearities and associated thresholds in the climate-permafrost relationship affect the dynamics of ground thermal regimes and permafrost landforms.
2. Projections of future thermal and geomorphic permafrost characteristics revealed that the changing climate has a notable impact on near-surface permafrost extent, active-layer thickness and potential distributions of permafrost landforms. Suitable conditions for near-surface permafrost and its associated landforms are decreasing in area, particularly at the southern fringes of the permafrost domain. Of interest was the strong sensitivity of ALT, pingos and ice-wedge polygons to the amount of rainfall. Importantly, changing climatic conditions were projected to also promote suitable conditions for permafrost landforms in continuous cold permafrost with no predicted current occurrences.
3. The hazard potential due to degrading permafrost was realized in locations where a projected thaw was associated with hazard-susceptible ground conditions, especially high ground ice content. Based on the produced geohazard maps, ice-rich permafrost regions including continuous permafrost in northwest and northeast Siberia, the Yakutsk basin as well as central and west Alaska are potentially facing the heaviest hazardous development due to climate change.
4. The findings of this thesis underline the notable magnitude of climate change-induced changes to permafrost landscapes. Quantifications of the infrastructure at risk suggest that almost one million people and one-third of the current infrastructure in the Northern Hemisphere's permafrost region will be at high risk to near-surface permafrost thaw-related ground instabilities by the mid-century.

Importantly, these figures and subsequently their socio-economic implications may be much larger if rapid reductions to human-induced greenhouse gas emissions are not achieved.

5. The syntheses of available observational data on the permafrost characteristics and infrastructure, as well as geospatial data on environmental conditions allowed for geohazard mapping and quantifications of infrastructure at risk at an unprecedentedly high spatial resolution across the circumpolar area. Despite the limitations to the statistical equilibrium approach and data quality, the methodology has a high potential for performing climate-change impact assessments on multiple scales. An inherent advantage of the method is that it is readily applicable with increasingly available, open, observational and geospatial data on current and projected future environmental conditions.

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