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Impact of climate change on soil frost and future winter flooding

Conséquences du changement climatique sur le gel du sol et les futures inondations hivernales

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RÉSUMÉ

Le gel du sol amplifie la génération de ruissellement hivernal dans l'hémisphère nord et entraîne de grandes inondations et des dommages matériels car il agrandit la zone contributive en réduisant la capacité d'infiltration des surfaces perméables. Le changement climatique modifie le cycle hydrologique, en particulier dans les régions froides qui sont plus sensibles au réchauffement de la température que les régions tempérées en raison de ses impacts sur les précipitations hivernales et les modèles de fonte des neiges, et donc, affectant le gel et le dégel des sols. Le but de cette étude était d'évaluer les tendances à long terme de la formation de gel dans le sol dans différentes régions d'Islande (66°N). Le modèle SHAW (Simultaneous Heat and Water) a été utilisé pour simuler la température du sol et la profondeur du gel sur trois sites qui connaissent différentes conditions climatiques hivernales. Le modèle a correctement prédit la température du sol jusqu'à 1 m de profondeur à tous les sites d'étude pour 20 ans ($R^2 = 0,90-0,96$). Les résultats montrent que la profondeur du gel et la température du sol diffèrent considérablement d'un site à l'autre. La température du sol a augmenté au cours des 74 dernières années à deux sites côtiers (0,015°C/an) significativement sur le plan statistique. La profondeur maximale annuelle de gel a diminué à un taux de 0,18 à 0,21 cm/an. Les premiers résultats de cette étude suggèrent que les gels du sol sont très variables et doivent être pris en compte pour l'évaluation des futures risques d'inondation. Un modèle numérique est un outil important pour surpasser la pénurie de mesures de sol.

ABSTRACT

Soil frost amplifies winter runoff generation in the northern hemisphere and leads to large floods and property damages by enlarging the contributing area because of a reduced the infiltration capacity of permeable surfaces. Climate change is altering the hydrological cycle, especially in cold regions that are more sensitive to temperature warming than temperate areas due to its impacts on winter precipitation and snowmelt patterns, and thus, affecting soil freezing and thawing. The goal of this study was to assess the long-term trends in soil frost formation in different regions of Iceland (66°N). The Simultaneous Heat and Water (SHAW) model was used to simulate soil temperature and frost depth at three sites experiencing different winter climatic conditions. The model accurately predicted soil temperature within the 1 m horizon at the studied sites over 20 years ($R^2 = 0.90-0.96$). Frost depth and soil temperature differed substantially between locations in the South and North/East. Soil temperature increased at statistically significant rate (0.015°C/year) at two coastal sites in the past 74 years. The maximum annual frost depth decreased at a rate ranging from 0.18 to 0.21 cm/year. The initial findings of this study suggest that soil frost is site specific and need to be accounted for when evaluating future flood risks. Numerical modeling is an important tool for overcoming the shortage of soil measurements.

KEYWORDS

Climate change, cold climate, flooding, frost, runoff

1 INTRODUCTION

Cold regions hydrology is largely governed by snowmelt and infiltration into seasonally frozen soil that influences surface runoff generation (Aygün et al., 2020). That said, little emphasis has been placed on winter conditions, even in northern cities, for example in planning-designing and operating drainage systems (Maksimovic et al., 2000). Climate change is heavily influencing winter hydrological processes in cold regions, intensifying rainfall amounts, snowmelt rates, and increasing the frequency of rain-on-snow events and soil freeze-thaw cycles (Würzer et al., 2016). Rain-on-snow events are characterized by a rapid release of melt water (Garvelmann et al., 2014), and when occurring simultaneously with soil frost, can produce large floods and great number of flooded properties in urban areas (Andradóttir et al., 2021). Soil frost is also a key factor that influences the efficiency of sustainable urban drainage systems (SUDS), which mostly rely on infiltration (Zaqout et al., 2022). Therefore, a successful implementation of SUDS in cold climate need to take soil frost susceptibility (Zaqout et al., 2022) and spatial variability into account (Boyer et al., 2010). Therefore, a better understanding of the changes in soil frost is essential for flood risk assessment and to accurately predict future runoff generation. The goal of this study, therefore, was to quantify the long-term trends in frost formation and soil temperature in three regions in Iceland using historical records and numerical modeling, to overcome the scarcity of soil observations.

2 METHODS

2.1 Study sites and data available

Iceland is situated close to the Arctic Circle in the North Atlantic Ocean. The climate is heavily influenced by the Gulf Stream which warms up the south and western coast. The capital of Iceland, Reykjavík, has maritime winter climate, characterized by frequent freeze-thaw and rain-on-snow cycles (Andradóttir et al., 2021). The northern and northeastern parts of the country experience colder winters with snow present 50-70% of the time (from October to May), as compared to 15-38% along southern coast (Einarsson, 1984). Three sites representative of different climatic conditions (Fig. 1) were chosen based on the availability of decadal soil temperature measurements and weather data conducted by the Icelandic Meteorological Office (IMO, 2022), which included ten-minute soil temperature, air temperature, relative humidity, wind speed, precipitation, and incoming solar radiation. They include the main urban monitoring site in Reykjavík, the capital of Iceland; Möðruvellir site located in an agricultural watershed; and Hallormsstaður in a forested and agricultural watershed.

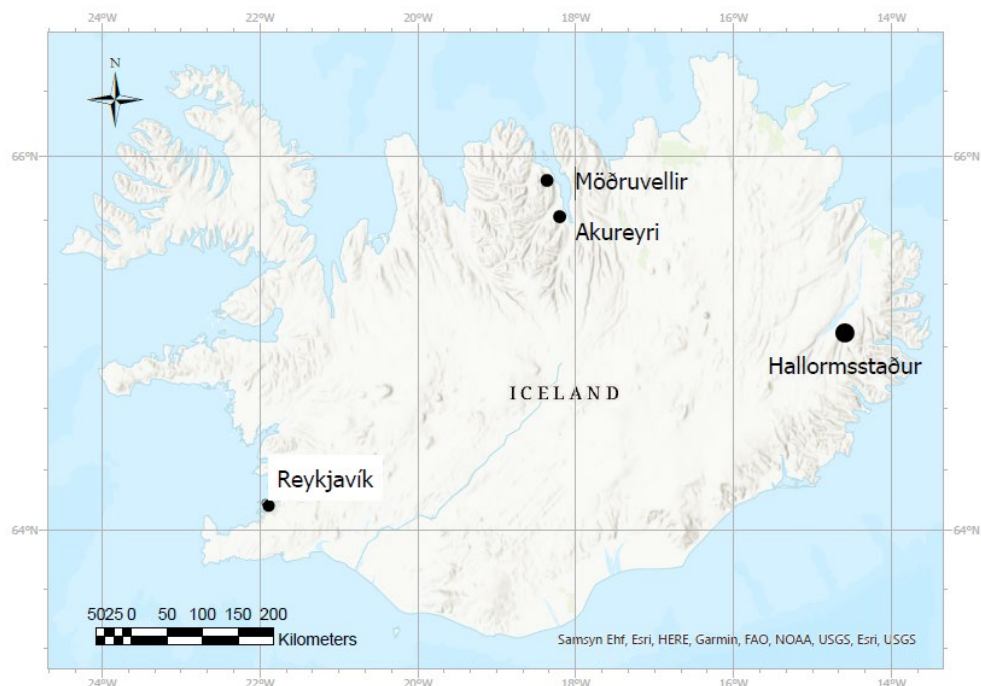


Figure 1 Study sites in Iceland where soil temperature, weather, and radiation data have been collected.

2.2 Numerical modeling

The physically-based, one-directional (1D), Simultaneous Heat and Water (SHAW) model was used to model soil temperature at the three study sites (Flerchinger & Saxton, 1989). The SHAW model has been widely used to model heat, water, and solute transfer, especially in soils undergoing frequent freezing and thawing (Flerchinger & Saxton, 1989). The key model outputs are soil temperature, moisture content (liquid and ice) at different pre-defined layers, and frost depth in the soil. The model was first calibrated and validated based on hourly data over 10–20 years. The model was then run using diurnal meteorological data to create a long-term historical record of soil temperature and frost depth.

2.3 Data analyses

The long-term trends in soil temperature and frost depth at the three studied sites were determined using the non-parametric Mann-Kendall test and the significant slopes using the Theil-Sen method. The statistically significant differences among the three tested sites were determined using the analysis of variance test (ANOVA), and the Student's *t* test was used to test the statistical differences between each of the sites. A significance level of 0.05 (confidence level of 95%) was chosen for all analyses.

3 RESULTS AND DISCUSSION

3.1 Modeling and performance evaluation

The soil temperature dataset available for each site was split into two sets (calibration and validation; Table 1). Overall, the model performed very well at all locations ($R^2=0.90-0.96$) and all simulation depths. The best results were obtained at Möðruvellir and Hallormsstaður for both calibration and validation periods. It is noteworthy that using the cloud cover from Akureyri station (Fig. 1) to estimate solar radiation at Möðruvellir (similar to method described by Bras (1990)) produced very good results.

Table 1 Summary of the SHAW model performance evaluation metrics at the study locations.

Site	Reykjavík		Möðruvellir		Hallormsstaður	
Soil depth (cm)	10, 20, 50, 100 cm		10, 20, 50, 100 cm		10, 20, 50, 100 cm	
Weather data duration	1949–2018		1949–2022		1950–1990, 2008–2021	
Calibration/validation	2007-2013	2013-2018	1996-2006	2006-2016	2008-2014	2014-2021
R^2	0.93-0.94	0.90-0.91	0.92-0.95	0.94-0.95	0.95-0.96	0.94-0.95
RMSE (°C)	1.47-1.86	1.53-2.83	1.49-2.23	1.34-1.49	0.82-1.04	0.84-1.17

3.2 Historical modeled soil temperature and frost

The initial model results of this research suggest that the maximum frost depth at the site in southwest Iceland (i.e., Reykjavík) was statistically different from both Möðruvellir and Hallormsstaður sites (which did not statistically differ from each other; Fig. 2): Frost was found to be twice as deep in Möðruvellir and Hallormsstaður (avg. = 31 and 28 cm) compared to Reykjavík (avg. = 15 cm). The annual minimum soil temperature in Möðruvellir (avg. = -1.14 °C) was significantly lower than in Reykjavík (avg. = -0.64 °C) but did not statistically differ from Hallormsstaður (avg. = -1.02 °C). The annual maximum frost depth and the annual minimum soil temperature were found to significantly trend both in the South and North, but not at Hallormsstaður (Fig. 2f). It is noteworthy that the rate of change in frost depth and soil temperature (see slope *s*; Fig. 2) were similar at the three sites. While frost depth was found to decrease, which may suggest that it is becoming less relevant for urban flooding, there are no indications that winter floods will become more benign in the next decades. Conversely, the timing of maximum soil frost was found to shift, coinciding with mid-winter RoS and snowmelt events (January–March; Zaqout et al., 2023). This, combined with the increase in the magnitude and frequency of RoS events (Andradóttir et al., 2021), suggests that winter floods may intensify, at least in the next decades. The reduction in soil frost in the colder parts of Iceland (i.e., North and East) also indicate that the increase in winter temperatures and precipitation in those regions might transform the local climate (becoming more temperate, similar to the south), which would increase the occurrences of RoS-induced flooding (Garvelmann et al., 2014).

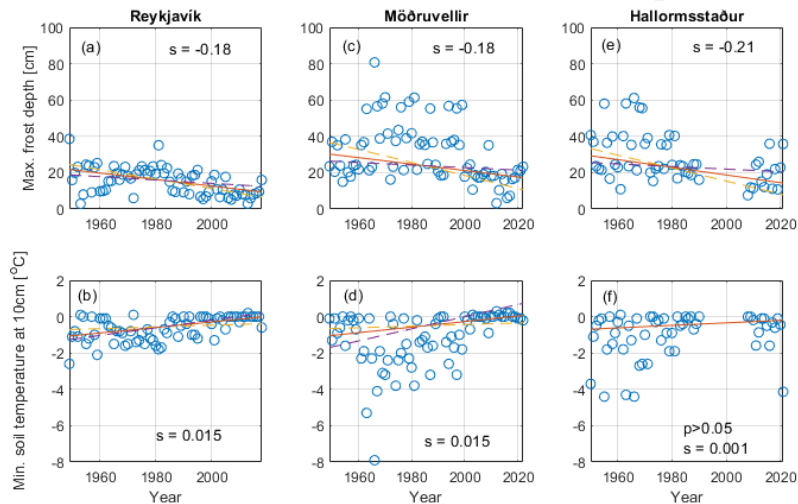


Figure 2 Trends in maximum frost depth and minimum soil temperature at the three study sites: (a), (b) Reykjavík, (c), (d) Möðruvellir, (e), (f) Hallormsstaður. S = slope. The solid line is Sen's slope, and the dashed lines represent the upper and lower 95% confidence intervals of the slope.

4 CONCLUSIONS

The initial results of this research highlight that soil temperature and frost depth can vary considerably by region, but that the long-term trends associated by climate change may not be as sensitive. A numerical model, such as SHAW, was found to be a helpful tool to understanding soil response to changing climate and overcome the lack of long-term records.

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