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学位論文内容の要旨

Aufeis is a prevalent phenomenon in the Northern Hemisphere, and several aufeis formations occur every winter in Ulaanbaatar, the capital of Mongolia. Ulaanbaatar is the coldest capital city in the world and is home to the majority of the country's population. Although Mongolia has a vast territory, its harsh climate and overconcentration of the population make aufeis a recurring hazard that causes significant damage to urban residents and city infrastructure each year. In recent years, rapid urbanization and population growth have expanded settlement areas and infrastructure; however, newcomers and construction have often been developed without adequately considering natural processes, their impacts, or associated risks, thereby worsening the situation.

Aufeis formation is a complex process influenced by a wide range of factors, including climate, meteorology, geological conditions, soil properties, permafrost distribution, hydrological system, and ground topography. As a result, the spatial distribution of aufeis varies from year to year. Although municipal authorities, institutions, and households take various measures in areas at high risk of aufeis formation, these efforts have been largely ineffective. Despite its annual recurrence, the processes driving aufeis formation and the natural factors that control its development remain insufficiently understood. Therefore, understanding how aufeis forms and what governs its spatial and temporal dynamics is essential. This requires detailed field investigations and measurements to characterize the origin, formation processes, and spatial distribution of aufeis in relation to geological conditions, soil properties, and climatic factors.

The objective of this study is to examine the long-term dynamics of aufeis and identify the natural factors regulating its extent and spatial distribution. Using Landsat satellite imagery fro m 2009 to 2024, we analyzed the long-term spatial distribution of aufeis, and detailed monthly-dynamic mapping was conducted during the winter of 2023-2024 using unmanned aerial vehic le surveys. The results show that aufeis typically begins to form in November, reaches its max imum extent in March, and fully melts by May. Between 2009 and 2023, the aufeis area rang ed from 0.01 to 0.03 km^2.

Electrical resistivity tomography measurements revealed a fault located at the boundary between permafrost and bedrock, coinciding with the spring water source. Water chemistry analyses indicated relatively high hardness, confirming that the spring is fed by groundwater. The water temperature measurement indicates that the minimum temperature of spring water is 1.51 °C, confirming the perennial spring. A strong correlation was found between the temperature of the spring stream and air temperature, and the spring stream was confirmed to freeze during certain periods in winter. During winter, groundwater-fed spring flow gradually loses heat as it travels along the stream; once frozen, flow toward the pond becomes blocked, forcing water to emerge onto the

ground surface and freeze, forming aufeis annually. Water chemistry results showed hardness of 3.56 mg-eq/dm^3, 1.72 mg-eq/dm^3, and 1.80 mg-eq/dm^3 for spring water, river water, and pond outflow, respectively, indicating that the pond is supplied by both spring and river water. The spatial distribution of aufeis also suggests that the river contributes to aufeis formation.

Analysis of aufeis dynamics and climatic factors shows that the air-temperature regime has a limited influence on changes in aufeis area extent. One source of the Bumbat aufeis is a groundwater-fed spring, and aufeis derived from such sources is less sensitive to seasonal climatic variations. In contrast, summer precipitation plays a more notable role in influencing the extent of aufeis.

During the winter of 2023-2024, the aufeis expanded to 0.04 km²-1.5 to 5.5 times larger than during previous years-and encroached into settlement areas, causing severe damage. The expansion of aufeis and changes in its spatial distribution destroyed many households' yurts, furniture, and belongings, rendering them unusable and forcing numerous families to relocate. Snowfall during the 2023-2024 winter was exceptionally high compared to previous years. In areas with annual aufeis formation, freezing n-factor values ranged from 0.05 to 0.11, clearly demonstrating the insulating effect of the snow cover. This thick snow layer prevented ground freezing and allowed spring water emerging onto unfrozen surfaces to flow toward and accumulate within the settlement area. In some households, soil water also surfaced beneath yurts and pit latrines, contributing to additional aufeis expansion.

Chemical analysis of the aufeis samples revealed elevated NH_4 concentrations exceeding background levels, indicating that wastewater from pit latrines had migrated to the surface and contributed to the expansion of the aufeis area. Wastewater from human activities accumulates in pit latrines, increasing NH_4 levels in soil water. As a result, NH_4-contaminated aufeis may pose health risks to residents in the affected areas and the broader urban population.

Changes in the spatial distribution of urban aufeis reduce living comfort for residents, damage infrastructure, buildings, and roads, and impose significant economic losses. This study enhances the methodology for effectively investigating aufeis through the combined application of remote sensing and field measurements and is important for mitigating the adverse impacts of aufeis in urban environments.

審査結果の要旨

本論文では，モンゴル国ウランバートル市において毎冬発生し，住民の生活や都市インフラに深刻な被害をもたらすアウフアイス現象を対象として，その形成過程および空間的・時間的分布特性を明らかにしている。2009年から2024年までの衛星画像解析と，2023〜2024年冬季に実施した無人航空機（UAV）による詳細調査を組み合わせ，アウフアイスの長期的変動および季節的成長過程を把握している。

さらに，電気探査や水温・水質分析等の現地観測により，地下水を起源とするアウフアイスの形成メカニズムを解明するとともに，降雨や河川水がその規模や分布に与える影響を明らかにしている。特に，多雪条件下における積雪の断熱効果が地盤凍結を抑制し，アウフアイスが居住域へ拡大する被害メカニズムを示している。

これを要するに，申請者は，都市域におけるアウフアイスの形成要因とその動態を体系的に解明し，寒冷都市におけるアウフアイス災害の理解と軽減対策に資する極めて有用な知見を示したものであり，将来の都市防災およびインフラ計画への貢献は大なるものがある。

よって，申請者は北見工業大学博士（工学）の学位を授与される資格があると認める。