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A local climate perspective on possible development pathways for Longyearbyen, Svalbard

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Review Article

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Abstract

Arctic human settlements experience formidable challenges from accelerating climate change and environmental transformations. While these towns have demonstrated adaptive resilience, the looming threat of local climate extremes raises concerns about the results of adaptation and mitigation efforts. With the further development of Arctic settlements, it is necessary to consider changes in local climatic conditions, shifting the adaptation focus from regional to local scales. The local climate perspective in this literature synthesis study is built upon constraints from physical climatology, focused on the climate and environment within and around the town of Longyearbyen, Svalbard. The study provides insights into Longyearbyen's local climate dynamics, including physical mechanisms, climate localisation, factors and trends, as well as their implications. Three model pathways for development are discussed, centred on (1) industrial development, (2) public services, and (3) tourism and conservation. This categorisation is introduced to distinguish development scenario sensitivity to the local climate effects. The synthesis indicates that any development concentrated spatially will amplify local warming and climate change, as positive climate feedback predominate. The study emphasises the need for a comprehensive understanding of the environmental factors sustaining local climatic anomalies.

Introduction

Climate change influences the long-term trends of temperature and weather patterns on global and regional scales. At local geographical scales from 1 km to 100 km, its impacts are not only significant but also more profound, especially in the Arctic (Stuecker et al., 2018). The effects of climate change on global and regional levels have been the focus of attention, whereas local climate effects have yet to be generalised or summarised. Fundamental questions relate to the physical mechanisms behind locally amplified climate extremes and the degree to which local extremes may exceed regional climate change. These and similar research questions are frequently addressed in physical and human geography (Hancock, Prokop, Eckerstorfer, & Hendrikx, 2018; Streletskiy, Suter, Shiklomanov, Porfiriev, & Eliseev, 2019; Suter, Streletskiy, & Shiklomanov, 2019). However, only fragmentary work has touched on physical climatology (Zhang et al., 2018). This study aims to address these questions by synthesising a local climate perspective from fragmented publications scattered across diverse disciplinary studies. We focus on physical climate change and its effects on the physical environment within and around the town of Longyearbyen, Svalbard. We analyse the density of in situ and high-resolution satellite observations and detailed research studies sufficient to distinguish between climate trends in closely situated locations. We then investigate the influential climate parameters and physical mechanisms and evaluate the magnitude of their local modifications, factors and trends. Finally, we discuss the implications of the local climate perspective for different development pathways for Longyearbyen and Svalbard. This is important for bridging the gap between physical and societal sustainability transformations in the Arctic.

The Arctic was – and still is – an inhospitable and remote region with a cold climate and harsh weather. The Arctic region is undergoing influential environmental transitions, and regional warming is accelerating (Taylor et al., 2022) and is more than four times stronger than the global average (Overland, Wang, Walsh, & Stroeve, 2014; Rantanen et al., 2022; Isaksen et al., 2022b). This amplification is reflected in many essential climate variables and environmental indicators (Box et al., 2019), particularly in sea ice retreat and multiyear ice disappearance (Liu, Key, Wang, & Tschudi, 2020). Evidence of ecological transitions (Myers-Smith et al., 2020), coastal erosion (Jaskólski, Pawłowski, & Strzelecki, 2018), and destabilisation of frozen grounds under infrastructural objects (Hjort et al., 2018) are found all over the Arctic.

Svalbard is a High Arctic archipelago at the northernmost reaches of warm Atlantic Waters at about 80°N – it is at the forefront of climate and environmental change (Hanssen-Bauer et al., 2019). Exceptional warming has been found across and to the east of Svalbard

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(Isaksen et al., 2016, 2022b). Due to local environmental changes in Svalbard, risks to infrastructure, ecological habitats, and human adaptation are increasing (Winther & Gudmestad, 2023). Although non-climatic factors dominate the ability of Arctic communities to adapt to and mitigate climate change (Ford, McDowell, & Pearce, 2015), this significant local increase in Arctic warming exacerbates the vulnerability of Svalbard communities. (Hestnes, Bakkehøi, & Jaedicke, 2016; Hovelsrud, Kaltenborn, & Olsen, 2020). There is an urgent need for research to address local climate change in Svalbard, especially since traditional engineering methods of "techno-fixing" are ineffective against locally intensifying changes. (Winther & Gudmestad, 2023).

The longest temperature record in the High Arctic has been established for Longyearbyen, extending more than a century (Nordli et al., 2020). The record reveals winter warming exceeding +10°C since 1991 and amplified warming across all seasons (Nordli et al., 2020). Summer heatwaves in 2020 (Dobricic, Russo, Pozzoli, Wilson, & Vignati, 2020; Overland & Wang, 2021) and 2022 (Nilsen, 2022) broke climatic temperature records in many Arctic places. Longyearbyen recorded its record-high temperature of +21.7°C on 25 July 2020, as documented at the Svalbard Airport station. That heat event had profound consequences. Built into permafrost, the Svalbard Global Seed Vault, where thousands of crop seeds are stored, is threatened by thawing permafrost. (Vaughan, 2020). Mine 7, which produces 60,000 tons of coal annually for export and the local coal-fired power station, temporarily ceased operations after being damaged by flooding (Jonassen, 2020). This seemingly well-protected underground mining was surprisingly sensitive to climate warming. Those examples manifest the vulnerability of the biophysical and human environment to locally amplified climate extremes. A crucial inquiry emerges regarding the potential of local climate changes to elevate vulnerability within Arctic societies and surpass resilience thresholds in their physical environments.

Meyer (2022) recognised a "techno-fix" bias in current adaptation practices in Longyearbyen. These practices imply a narrow understanding of adaptation and do not address the more challenging task of transforming society. Simultaneously, Winther and Gudmestad (2023) warned that a techno-fix would require innovations as traditional techniques may fail under the combined pressure of locally amplified geohazards, e.g. increasing coastal erosion, soil moisture, and permafrost thaw. Ignoring local climate prospects can cause maladaptation and negative consequences. Place-based knowledge is crucial for successful adaptation (Fedorov, 2019; Meyer, 2022). Following studies in ecology (Colloff, Wise, Palomo, Lavorel, & Pascual, 2020), maintenance of a declining resource, e.g. permafrost maintenance with a thermosyphon technology (Aftret & Daleng, 2022), might become a case of maladaptation in Longyearbyen.

Since the 1990s, climate issues have become essential for the Arctic urban development agenda (Petrov et al., 2016; Shiklomanov, Streletskiy, Swales, & Kokorev, 2016; Orttung et al., 2017). Some Arctic towns, such as Utqiagvik (formerly Barrow, Alaska), may have to relocate (Lynch & Brunner 2007); others, such as Norilsk (Russia), have to restructure and rebuild (Shiklomanov, Streletskiy, Grebenets, & Suter, 2017). For some towns, such as Vorkuta (Russia), the effects of combined socio-economic and climate changes are overwhelming (Shiklomanov, Streletskiy, Suter, Orttung, & Zamyatina, 2020; Kotov & Khilimonyuk 2021). Under increasing socio-economic pressure, local climatic factors are becoming critical for proper adaptation to climate change. A *local climate perspective* is a perspective that focuses on the specific climate conditions and patterns of a smaller geographic area. In the context of Longyearbyen, the town faces one of the strongest climatic warming followed by influential environmental changes (Vickers et al., 2016). The warm West Spitsbergen Current keeps the ocean to the southwest of the islands free of sea ice (Frank, Jonassen, Skogseth, & Vihma, 2023). It makes Longyearbyen logistically more accessible than other parts of the Arctic, facilitating tourism development (Bystrowska, 2019), mineral resources, and fisheries exploitation (Stocker, Renner, & Knol-Kauffman, 2020). Two processes – climate change and socio-economic shifts – shape Longyearbyen´s concerns and debates (Hovelsrud et al., 2020, Meyer, 2022). Climate change is a global issue that affects local communities differently. To effectively address the issue, it is crucial to consider every community's distinct outlook and necessity. This synthesis study looks at how local climate impacts can shape development pathways. Researchers have been exploring the co-effects approach, which considers the interconnectedness of different climate impacts. For example, Dannevig et al. (2023) studied the effects of climate change on nature-based tourism in Svalbard and found that it can have cascading impacts. Winther and Gudmestad (2023) reviewed the local climate problems in Longyearbyen and suggested ways to address them.

Our study examines local perspectives on physical climatology by selecting and analysing the literature on the main climate variables in the Longyearbyen area. We reviewed all relevant papers and several technical and student reports, which can be found by searching Google Scholar™ requests (63 records in total as of August 2, 2023). The literature search query is based on terms related to "local climate," "meteorology," "observational data," and the like. We considered publication providing for climate variables at spatial scales finer than 10 km around the Longyearbyen. If there is a chain or a nest of related publications, we consider only the most relevant publications to elucidate physical mechanisms. In this study, we have examined the references related to essential climate variables that are considered influential factors in Longyearbyen's societal transformation. We acknowledge that the references outside physical climatology are patchy and subjective. However, our objective is to identify publications that can bridge the gap between physical and societal sustainability transformations.

Understanding Longyearbyen's unique climate: geographical features, weather patterns, and environmental impacts

Longyearbyen (78°13'N, 15°38'E) is a town of unique geographical and climatic features. It is located on Spitsbergen, the largest island of the Svalbard archipelago (Fig. 1). At this latitude, the polar night lasts from November 14 to January 29, and the midnight sun lasts from April 20 to August 22. The town, with a population of about 2,300, is nestled in a narrow, steep-sided valley on the southern side of the Adventfjorden, the entrance to the larger Isfjord that opens into the Atlantic Ocean on the western side of Svalbard. The mountains surrounding the city exhibit flat, ice-covered peaks and steep, crumbling slopes, which significantly influence local temperature contrasts and spatial differences in snow accumulation and soil moisture. The prevalence of permafrost necessitates the construction of buildings on piles for improved ventilation above frozen ground (Bekele & Sinitsyn, 2017), and all communications and utilities require additional insulation. The

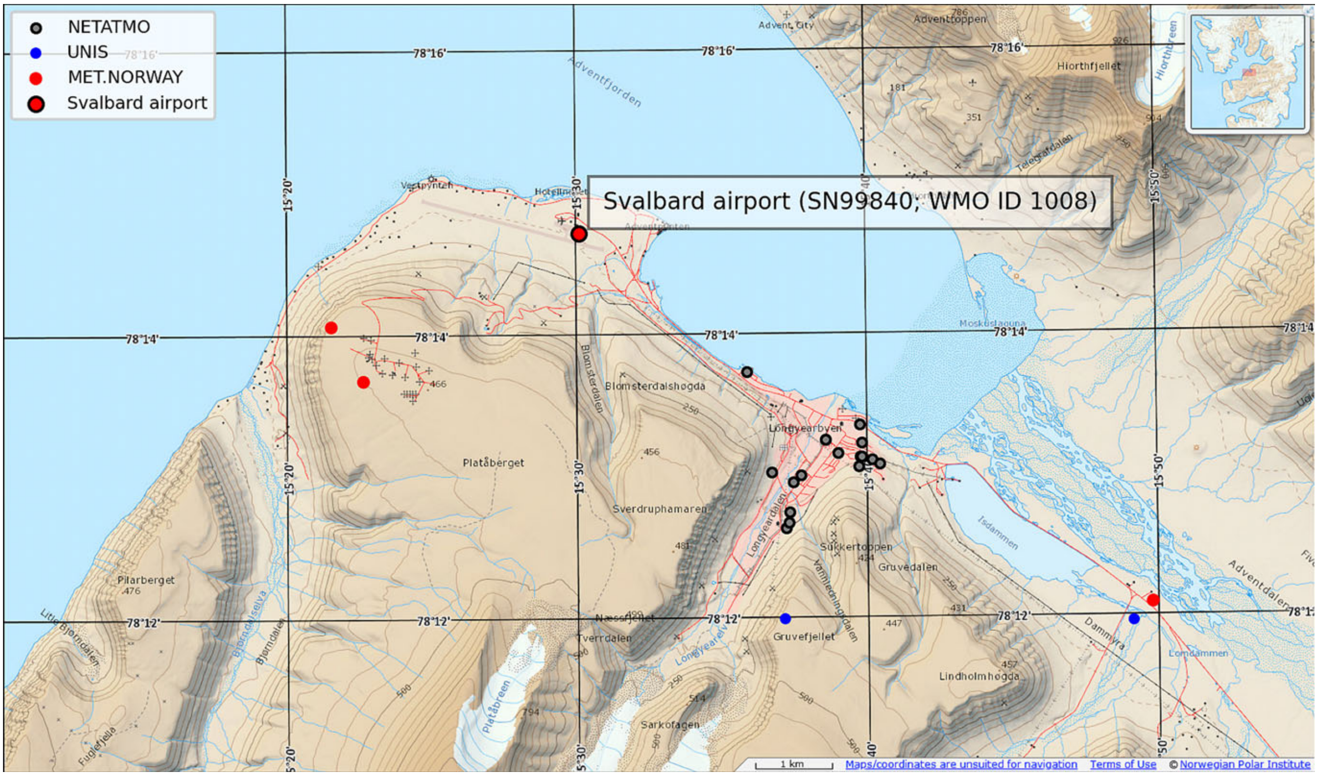

Figure 1. The map of Longyearbyen and its surrounding area with identified locations of observational sites. The main station at the Svalbard airport is shown as a red dot with a black circle. Stations of the Norwegian Meteorological Institute (MET.NORWAY) are shown in red; stations of the University Centre in Svalbard (UNIS) – in blue; and the private citizens' stations NETATMO – in grey. The background topographic map is taken from TopoSvalbard (https://toposvalbard.npolar.no; The Norwegian Polar Institute).

West Spitsbergen Current, with its relatively warm waters, plays a crucial role in keeping sea ice away from the coastline, although not at a considerable distance (Frank et al., 2023), thereby influencing the local climate of Longyearbyen.

Svalbard's climate is categorized as a polar tundra (ET) climate under the Köppen-Geiger classification system. (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006). Numerous research works have established connections between the long-distance meridional transfer of heat and moisture and the fluctuations in daily air temperature and precipitation patterns in Svalbard (Osuch & Wawrzyniak 2017; Pithan et al., 2018). The meridional heat transport in the mid-atmosphere (3–7 km above the ground) is a key mechanism supporting the lower atmospheric stability and local climate anomalies (Feldl, Bordoni, & Merlis, 2017; Stuecker et al., 2018; Esau et al., 2023). The local climate experiences alternating impacts of the western (wet and cool) and eastern (dry and cold) climate regimes (Esau, Argentini, Przybylak, Repina, & Sjöblom, 2012; Pilguj, Kolendowicz, Kryza, Migała, & Czernecki, 2019; Łupikasza, Niedźwiedź, Przybylak, & Nordli, 2021). There are also regular climate differences on the local scales. The mildest climate is found along the western coast (Vikhamar-Schuler, Lutz, & Gjelten, 2019). The mean temperature drops considerably in the inner and eastern parts of the island, for example, along the Svalbard Airport-Advent valley axis over just a few kilometres (Gjelten et al., 2016). This land-sea temperature gradient drives the Advent Valley´s local winds (breeze) (Henkies, Høyland, Shestov, Duscha, & Sjöblom, 2023). Summer temperatures in Longyearbyen remain above freezing, and the melting season (122 days on average during 1991–2018) is surprisingly long for such high latitudes. The 21st century has witnessed warm winters, coinciding with the reduction (from 50% to less than 10%) of the sea ice cover in Isfjorden (Nilsen, Cottier, Skogseth, & Mattsson, 2008; Muckenhuber, Nilsen, Korosov, & Sandven, 2016).

Advancements in satellite observations, data synthesis, and modelling for studying Svalbard's local climate

Unlike global, pan-Arctic, and regional assessments, local climate information is often fragmented and overlooked (Hanssen-Bauer et al., 2019). An essential component of local climate research is satellite observations. Recent advances in polar-orbiting satellite observations have made remote-sensing products indispensable for Arctic climate research (Esau et al., 2023). Local climate studies benefit from satellite observations, allowing monitoring of large areas at metre-scale spatial resolution (Duncan et al., 2020). The Svalbard Integrated Arctic Earth Observing System (SIOS) is an international consortium developing an efficient observing system for long-term in situ measurements and remote sensing in Svalbard (Jawak et al., 2023). Satellite platforms (e.g. the Sentinel and Landsat series) provide data in multiple wavelength bands at metre-scale resolution. The data could be openly accessed through SIOS, COPERNICUS, and Earth Observer initiatives. Another component of local climate research includes a network of routine meteorological and ground-based observations (Wickström, Jonassen, Cassano, & Vihma, 2020) and networks of low-cost, amateur-grade environmental sensors that enhance local observation capabilities (Hintz et al., 2021). The final component is high-resolution modelling, becoming increasingly available and popular (Kilpeläinen et al., 2012). As Earth modelling technology advances, the concept of 'digital twins' is emerging as a potential game-changer for informed environmental management (Bauer et al., 2021). In the context of Earth modelling, a digital twin is essentially a representation of the Earth's natural systems.

This study's most important data sources are provided in the Norwegian Centre for Climate Service report "Climate in Svalbard 2100" (Hanssen-Bauer et al., 2019). The report is an expert synthesis of observational data and climate change projections from the regional climate perspective. The report combines current knowledge of Svalbard's climate based on original datasets and regional downscaling of the global climate model simulations (Vikhamar-Schuler et al., 2019). It includes results from numerous climatological and environmental publications. However, it does not focus on actionable scales – the spatial scales of 0.1 km–10 km at which climate adaptation measures directly affect the physical environment. The local climate perspective can be constructed for Longyearbyen because this area is densely covered with climate and environmental observations. Many of these datasets can be retrieved from SIOS, an international observing system for long-term measurements in and around Svalbard (https://sios-svalbard.org/, last accessed 10.07.2024). Archived historical meteorological datasets are accessible on MET Norway's websites, frost.met.no and seklima.met.no. Nordli et al. (2020) published the central climatic-quality instrumental temperature records. In addition, two atmospheric reanalysis datasets are available: The Sval-Imp dataset with 1 km × 1 km spatial resolution, which is derived from downscaling the ERA40 and ERA-Interim reanalyses, and the COSMO climate model simulations with 2.5 km × 2.5 km spatial resolution which are driven with ERA-Interim reanalysis data.

Insights into Longyearbyen's local climate dynamics: physical mechanisms and climate localisation

Certain regions are experiencing more pronounced effects of climate change due to specific primary physical mechanisms. Climate change localisation is notably linked to the absence of atmospheric mixing, which maintains the spatial patchiness of surface physical and geomorphological properties in the atmosphere immediately above the surface. For example, adjacent land patches of snow and bare soil can maintain climatically significant temperature differences of several degrees (Johansen & Tømmervik, 2014). Significant climatic differences exist between open water, sea ice, land, and glacier surface adjacent to each other. Figure 2 shows the local climate perspective in Longyearbyen and highlights the different elements, such as the vegetation index and land surface temperature. At low latitudes and more open terrain, spatial climatic differences are suppressed by intensive air convection or turbulence. The surface energy balance fails to sustain intensive turbulent mixing at high latitudes. This deficiency in mixing entraps local climatic differences near their points of origin, thereby gradually accumulating the impact of these differences on other components of the environment. The Normalised Difference Vegetation Index (NDVI) reveals how sensitive vegetation productivity is to the local climate variations (Fig. 2, domains A, B, and C). The active soil layer and permafrost accumulate the local temperature changes over decades, making knowledge of those differences necessary to predict changes. The complex terrain around Longyearbyen further contributes to climate localisation. Mountains trap air pockets within valleys and channel airflow in an intricate way that only fine-scale simulations could reveal (Kilpeläinen et al., 2012; Mayer et al., 2012; Hancock et al., 2018).

Both static and dynamic physical factors play a significant role in contributing to the local climate. The static factors, which collectively refer to physical processes and feedback attributed to the heterogeneity of the surface types (Goosse et al., 2018), are crucial. They relate to the diversity of radiative properties and heat capacity of the surfaces. However, these static factors cannot realise their potential without constraints from the dynamic factors. The most crucial dynamic factor is the restrictions on vertical and horizontal atmospheric mixing (Stuecker et al., 2018). These dynamical restrictions result in decorrelation (decoupling) between the local (boundary layer) and the regional (free atmosphere) climate processes. The atmospheric boundary layer decoupling is frequently observed in Longyearbyen (Mayer et al., 2012). Decoupling contributes to developing a set of local weather phenomena, such as winds, clouds, and turbulent air mixing. They are difficult to capture through meteorological modelling but influential enough for climate change adaptation solutions, e.g. for wind energy potential assessment (Henkies et al., 2023). Figure 2 illustrates this high degree of climate localisation. The regional climate was determined by the temperature contrast between Isfjorden, glaciers, and narrow valleys. Solar radiation absorbed by slopes is trapped near the surface as the atmospheric mixing weakens and cannot redistribute the heat. It allows temperature anomalies to be more persistent and significant than observed over more open landscapes.

Insights into Longyearbyen's local climate dynamics: factors, trends, and implications

Drivers and trends in Longyearbyen's climate dynamics

Two pivotal factors – the extent of open waters in Isfjorden and the persistence of cyclonic atmospheric circulation patterns – shape the local climate in Longyearbyen (Frank et al., 2023). While interconnected, these factors exhibit distinct links to the atmosphere and the ocean, engaging in the most intensive interactions across vastly different time scales. (Gulev, Latif, Keenlyside, Park, & Koltermann, 2013; Outten, Esau, & Otterå, 2018). The warm water penetration in the fjord is insensitive to seasonal atmospheric variability, whereas, by contrast, the local air temperature is sensitive to the presence of the open water surface (Nilsen et al., 2008; Skogseth et al., 2020). Cold winters occur when the penetration is limited and sea ice advances in the fjord; each 10% increase in the sea ice cover causes the mean winter temperature to drop by 0.4°C (Isaksen et al., 2016).

The local climate in Longyearbyen is experiencing a warming trend at a faster rate than the Arctic's on average, with the only place with even more extreme warming being within the marginal ice zone to the north and east of Svalbard (Isaksen et al., 2022b). The surface air temperature has risen sharply since the 1990s, influenced by quasi-periodic patterns lasting between 15 and 40 years (Årthun et al., 2017). Warming trends have been observed across all seasons throughout the entire period of observation, with statistically significant findings (Nordli, 2010; Nordli, Przybylak, Ogilvie, & Isaksen, 2014; Nordli et al., 2020). The winter/spring season has the most significant trend (0.43°C per decade), whereas the annual mean trend is 0.32°C per decade. Since 1991, Svalbard airport's temperature record has shown a warming trend of 1.7°C per decade. Between 1991 and 2018, the number of days colder than −20°C has decreased by 27 (62%). Since 1997, no mean summer temperature has been below the climate average from 1960 to 1990. Between 1991 and 2018, the number of days warmer

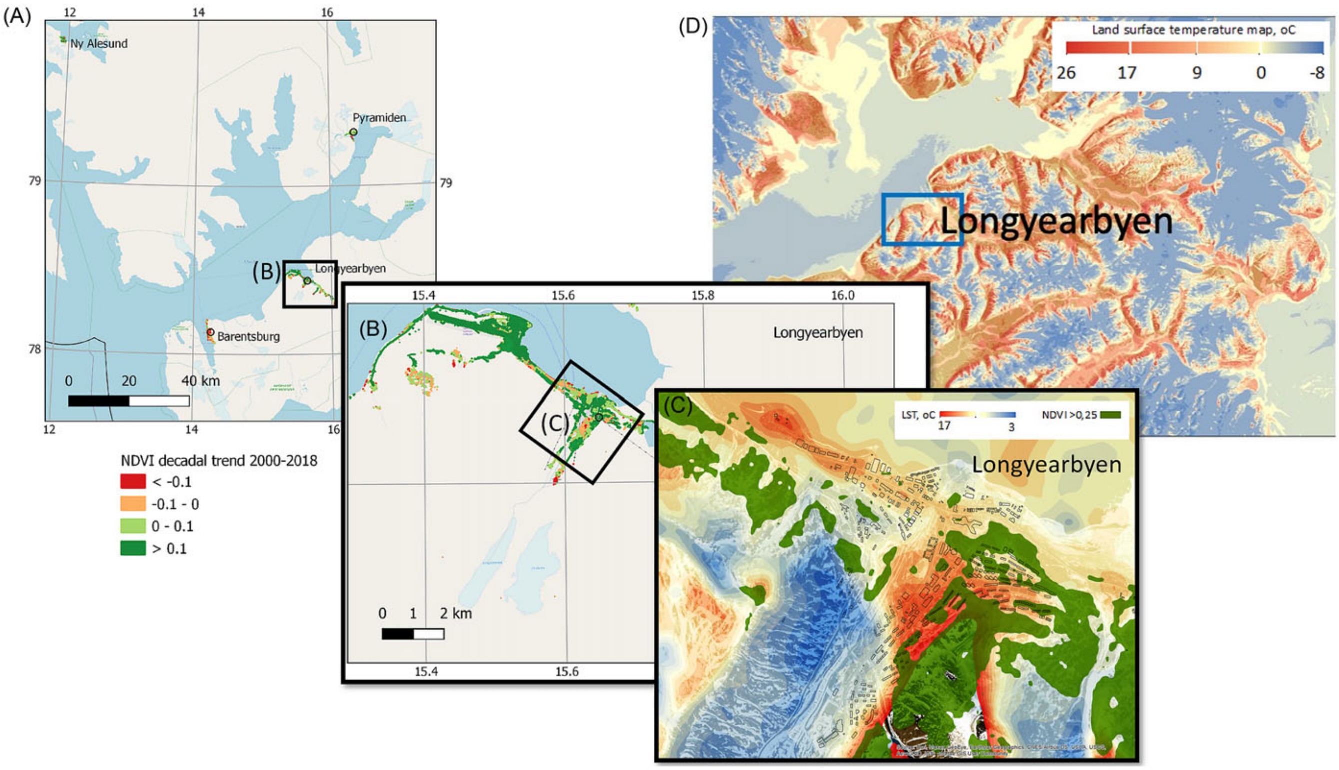

Figure 2. Elements (vegetation index and land surface temperature) of the local climate perspective in Longyearbyen. Land Surface Temperature (LST) and Normalised Vegetation Difference Index (NDVI) are retrieved from satellite observations. The domains (A) and (B) are taken from (Bartsch et al., 2021) and present the Sentinel-1 and –2 NDVI trend data. The domains (C) and (D) are own analysis and present the Landsat-8 images: LST – from the bands 10 and 11 (100 m spatial resolution); NDVI – from the bands 4 and 5 (30 m spatial resolution). The base layer shows urban infrastructure from OpenStreetMap data (https://download.geofabrik.de/).

than 0°C has increased by 25 (21%). According to (Hanssen-Bauer et al., 2019), local warming will continue in the 21st century. Additionally, in the RCP4.5 scenario, which is now considered a “business as usual” scenario, the temperature will increase by 5.4 ± 1.2°C by 2,100 (Hausfather & Peters, 2020).

Impacts of sea ice reduction and permafrost dynamics on climate and geohazards in Longyearbyen

The sea ice cover dramatically influences the local temperature increase in the surrounding area of Adventfjorden and the wider Svalbard region. Research shows that the mean annual temperature can increase by 8°C when sea ice concentration is reduced from 50% to 0% in the Svalbard region (Isaksen et al., 2022b). Locally, the mean winter temperature difference between the Svalbard Airport and Janssonhaugen stations increases by 5°C when fast sea ice disappears from Adventfjorden (Dahlke et al., 2020). It is worth noting that fast ice is a type of stationary sea ice that is anchored to the coastline and forms in shallow coastal areas. Unlike drifting sea ice that moves along with the water, fast ice significantly impacts the local climate as it reduces the air-sea heat and moisture exchange by 10× or more. Therefore, the disappearance of fast ice can drastically change the climatic conditions along the coast. Between 1974 and 2008, fast ice was present yearly at Barentsburg, closer to the fjord mouth (Zhuravskiy, Ivanov, & Pavlov, 2012). However, since 2006, there has been a significant decrease in fast ice periods (from November to May) due to late freezing (Dahlke et al., 2020; Skogseth et al., 2020). Although the transition to ice-free winters in Isfjorden improves marine logistics, it also makes the coastal area more vulnerable for erosion, landslides, and permafrost thaw (Jaskólski et al., 2018; Bartsch et al., 2021).

In the past 50 years, there has been an increase of 30–45% in annual precipitation, likely due to Arctic warming and increased moisture transport (Pithan et al., 2018; Gimeno, Vazquez, Eiras-Barca, Sori, Algarra, & Nieto, 2019; Rinke et al., 2019; Førland et al., 2020). The reduction in sea ice is also a significant factor affecting local air temperature and precipitation variability, with the amount of precipitation often corresponding with the level of sea ice retreat (Wickström et al., 2020). Rising temperatures and precipitation increase the risks of landslides and snow avalanches (Hestnes et al., 2016; Hancock et al., 2018). Climate simulations predict that precipitation will continue to increase by at least 28% or more (Hanssen-Bauer et al., 2019). Snow avalanches and land sliding are the most significant geohazards in Longyearbyen (Hestnes et al., 2016). The Norwegian Water and Energy Directorate (NVE) has created a hazard zonation map for area planning (Fig. 3), which shows that the most populated eastern slopes are in the high-risk zone for snow avalanches. Figure 2 (panel C) shows that this area also experiences the most significant land warming. Snowdrift across the extensive barren plateaus builds significant cornices on eastern slopes. These cornices eventually break down as cornice fall avalanches (45.2% of all avalanches). Slab avalanches are also frequent (32.6%) and account for the most significant observed avalanches, with more than 80% of the total snow mass (Eckerstorfer & Christiansen, 2011). Although the hazard warning system has been significantly improved (Engeset, Landrø, Indreiten, Müller, Mikkelsen & Hoseth, 2020), a perspective hazard assessment that uses climate change projections has not yet been realised. Predicting snow avalanches requires mapping local

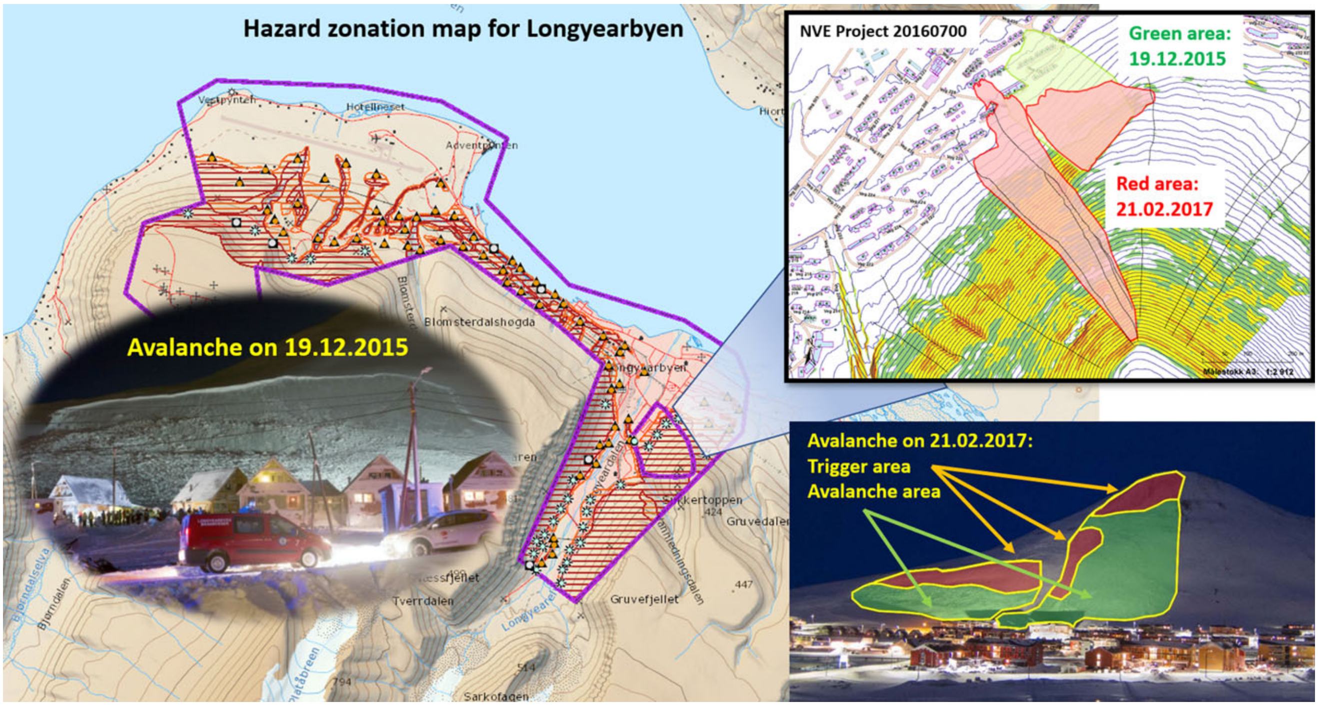

Figure 3. Hazard zonation map for Longyearbyen available from NVE (https://temakart.nve.no/link/?link=faresoner&layer=5&field=KOMMNAVN&value=Spitsbergen&buffer=100), see also methods in (Engeset et al., 2020); inserts show two major snow slab avalanches in the town on December 19, 2015 and February 21, 2017. Both avalanches occur after severe snowstorms with easterly winds. Pictures are from the NVE report (Landrø et al., 2017); the avalanche location assessment is after (Eckerstorfer & Christiansen, 2011).

snow cover differences in thickness (snow accumulation and drift) and density.

The active soil layer and permafrost are the most localised and inertial elements in the local climate perspective. Permafrost is continuous and usually 100 m thick in Longyearbyen (Hjort et al., 2018). Since regular temperature monitoring began in 1998, permafrost at 15 m depth has warmed by 2°C over 20 years. This rise threatens permafrost stability as its temperature (varying between −2.6°C and −5.2°C depending on the site's landforms and snow cover) is already high and may reach the thawing point in a few decades (Winther & Gudmestad, 2023). Accumulating warming signals in inertial systems is well understood in climatology, but details are specific to each case (Instanes & Rongved, 2017; Isaksen et al., 2022a; Smith, O'Neill, Isaksen, Noetzli, & Romanovsky, 2022). Data from the Ny Ålesund station (Westermann, Lüers, Langer, Piel, & Boike, 2009; Westermann, Langer, & Boike, 2011) show that during clear-sky conditions in July, temperature disparities in wet and dry soil patches can extend up to 10°C, enabling the differentiation of frozen and thawing grounds. Weekly and monthly mean differences are minor but still reach 3–4°C. These temperature differences between frozen and thawing ground illustrate how human infrastructure, buildings, and land disturbances affect the local climate. Studies show that the accumulated degree-day totals of the snow-free period can differ by more than 60% within the town, reflecting significant microclimatic variations influenced by urbanisation and land-use changes (Westermann et al., 2011)

Temperature inversions and their implications on the complexity of local climate

The study in Longyearbyen found that during July and August, there was a positive turbulent sensible heat flux of $+22.5\ \mathrm{W\ m^{-2}}$. However, for the rest of the year, the mean annual turbulent sensible heat flux was negative ($-6.9\ \mathrm{W\ m^{-2}}$). This results in temperature inversions, where the air temperature increases with altitude because the surface is colder than the air above it. These temperature inversions occur due to the local climate's dynamic factors, significantly the persistence of temperature inversions in the valleys (Valkonen et al., 2020).

The area is unfortunately also prone to accumulating atmospheric pollutants at the surface level due to temperature inversions. In 2007, a 2-month monitoring campaign found high transitional concentrations of aromatic hydrocarbons, including benzene, toluene, and C2-benzenes (Reimann, Kallenborn, & Schmidbauer, 2009). The levels of these pollutants were comparable to those found in European towns during local rush hour (two diurnal peaks) in April and May, which is caused by snowmobile activity. Although snowmobiles emit relatively low levels of pollutants, diesel-fuelled heavy-duty vehicles, permanently used for coal transport from the adjacent coal mines, are the primary source of emissions.

The local climate is a complex and highly varied system characterised by the different surface properties that have a static impact on it. The effects of these static factors are less pronounced in lower latitudes, where atmospheric mixing and local air flows can help to dilute them. However, in the Arctic, where atmospheric stability is high, and the surface energy balance is negative, the impact of these static factors is more significant and dynamic. The local climate perspective is further complicated by the influence of temperature differences on the stability of snow cover and frozen ground, as well as on air quality and various geohazards. These geohazards pose significant risks to human activity, such as infrastructure damage, landslides, and other environmental hazards. Therefore, understanding the local climate is crucial for designing sustainable responses to geohazard risks and human

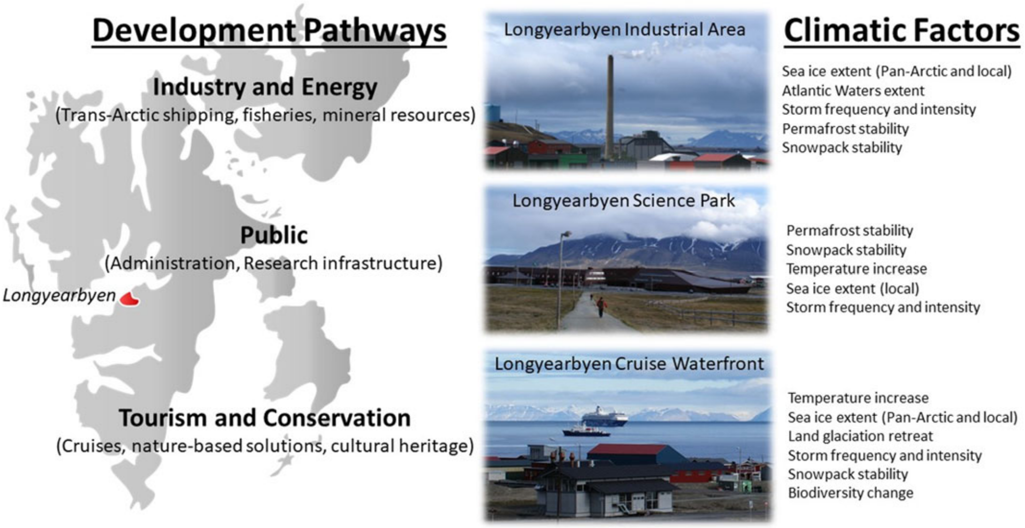

Figure 4. Graphical presentation of the study connecting three development pathways to influential climate factors. The Svalbard cartoon map from (https://www.subpng.com; by Vskuagtekt) is free for non-commercial use. Photos are taken by the authors. The cruise ship is "M/S Roald Amundsen."

activity. Accurately predicting the local climate's behaviour is essential for modelling the impact of human activity and making informed decisions about land use, resource management, and other critical issues.

Navigating sustainable development pathways in arctic towns while considering the local climate

Social sciences and humanities play significant roles in identifying sustainable and resilient development pathways for Arctic towns (Berman & Orttung, 2020; Orttung et al., 2017, 2021; Petrov et al., 2016). For Longyearbyen and Svalbard in general, tourism, education, and research are the three socio-economic pillars to which the transition from the coal-mining industry is stipulated (Hovelsrud et al., 2020). We organise the discussion along three (industrial, public, and tourism and conservation) pathways. This categorisation is abstract and subject to criticism, but it distinguishes impacts and feedback from the local climate effects. In our defence, we refer to three scenarios for the macro-development of Russian Arctic towns: Resource-Dependent, Self-Reliant, and Harmonious Arctic (Petrov et al., 2021). The main difference between these scenarios is the amount of human intervention in the physical environment. The industrial pathway directly exploits economic opportunities such as energy resources and fisheries. On the other hand, the other two pathways involve more nuanced human interactions with the environment.

Svalbard governance requires the tourism sector to preserve a fragile environment and protect the archipelago from the impacts of global change. The development focus on tourism, research, and education is a national priority for Svalbard. It distinguishes the adaptation context in Longyearbyen from other Arctic communities, as Hovelsrud et al. (2020) state. The Norwegian policy "supports extensive tourism while also stipulating strict protection of the environment that attracts tourists" (Hovelsrud et al., 2023). The problem is that geomorphological and climatic conditions in the Arctic, generally and in Longyearbyen specifically, do not allow for highly concentrated human activity. Such activity inevitably destroys the place's environment – its frozen state and cold climate. This is because the sum of the favourable climate feedback, which amplify climate warming, outweighs the negative feedback (Goosse et al., 2018). Indeed, any aerosol and black carbon (soot) sedimentation on pristine snow decreases its reflectivity (albedo) and accelerates melting; a darker surface absorbs more solar heat, which, with time, warms the ground and the lower atmosphere. Tourism is a component of industrial development, necessitating corresponding investments in public services and infrastructure. At the same time, the localisation of strong climate change in the Arctic could help protect its environment. The climatic impact of human activity is significant in the town but could also be limited to the town. The challenge lies in limiting the sprawl of activities to undisturbed areas, thus achieving a harmonious integration of these pathways to promote sustainable development in Svalbard. Figure 4 and Table 1 summarise the local climate factors and their impact.

The tourism and conservation pathway seeks to benefit from increasing interest in the Arctic environment (Aldao & Mihalic, 2020; Kugiejko, 2021). This is the most complex and controversial pathway as it involves balancing the value of pristine Arctic nature with the threat of climate change. A dominant perception of Svalbard is that it is Europe's last wilderness. The most valued environmental components are untouched nature, landscape, and cultural heritage left by the Arctic pioneers (Holmgaard, Thuestad, Myrvoll, & Barlindhaug, 2019). The increasing pressure of visitors on the natural environment along popular routes poses a challenge in protecting the nature tourists want to experience. Svalbard's policies aim to balance development with the conservation of nature. However, increased tourist activities make it vulnerable to local climate extremes. (Hovelsrud et al., 2020). Tourist operators must be flexible and adapt to the ever-changing demands of their customers. To achieve this, they extend the cruise season, change routes, and develop new tourism products (Hovelsrud et al., 2020: Dannevig et al., 2023). However, it is essential to have organised activity to ensure safety. The scale of this challenge has been demonstrated through the analysis of snow avalanches along snowmobile routes (Eckerstorfer & Christiansen, 2011; Hancock et al., 2018). The local climate perspective is indispensable in identifying and quantifying related vulnerabilities. Immediate and local impacts, such as snowmobile tracks, should be considered

Table 1. Consequences of climate change in Longyearbyen – a summary inspired by Table 2 in Hovelsrud et al. (2020); updated and corrected to account for the local climate perspective

Factor of climate change	Threats, Challenges, Opportunities	Adaptation measures and needs
Atmospheric warming	Increased precipitation (snowfall, rain-on-snow)	Intensified and more holistic hazard zonation, urban planning that includes the climate projections Reconstruction of port and town to accommodate larger number of tourists
	Increased snow accumulation and threat of massive slab avalanches,	
	Increasing need to adjust to and accept adverse weather conditions.	Change land-based tourist activity
Ocean warming and sea ice retreat	Enhanced coastal erosion	Change tourism routes, regulations and products
	Expansion of fisheries	Accommodation of larger ship traffic
	Improved accessibility; increasing shipping and tourism	
Ground warming	Permafrost thaw	Correction of building codes, improved maintenance measures
	Damage to buildings, infrastructure	
Ecosystem change	Acceleration of decay processes, methane, and carbon release	Build protection, zoning restrictions
	Affect psychosocial health and quality of life	Organisation of public space
		Ecosystem protection

from a climate perspective, such as accelerated permafrost degradation, as observed elsewhere (Gibson, Brinkman, Cold, Brown, & Turetsky, 2021). Improvements in specific climatic comfort indices could benefit Arctic tourism (Huang et al., 2021).

The industrial pathway must diversify and provide various economic services while sensitive to the local physical, environmental, and climate conditions. According to climate projections (Hanssen-Bauer et al., 2019), the Arctic warming scenario is expected to bring some benefits. These include the continued retreat of sea ice, which could make fisheries more economically viable. Longyearbyen is expected to become an increasingly crucial Arctic logistic and industry hub (Stocker et al., 2020). A recent study states that having a modern port in Longyearbyen is crucial (Nyman, Galvao, Mileski, & Tiller, 2020). Statistics for the Port of Longyearbyen (SPL, 2020) indicate that in 2019, the port was visited by 446 cruise and tourist ships, 78 cargo ships, and 16 fishing vessels.

The economic adaptation should prioritise self-sufficiency, cost reduction, and flagship projects for territorial status maintenance (Hovelsrud et al., 2020). A nexus sustainable renewable energy system is a feasible option in this direction. Ringkjøb et al. (2020) demonstrated the theoretical feasibility and economic viability of such a system. Solar radiation and wind energy resources enormously vary on local spatial scales and seasons (Solbakken, Babar, & Bostrøm, 2016). The local climate is essential for the system's implementation as it would provide information for balancing capacity. This system's observed increasing winter storminess could enhance energy generation, particularly in winter. In the 2022 state budget, a new energy plan for Longyearbyen urges the transition to renewable energy sources to overcome as the primary energy supply (Ødegaard, 2022). The coast between the new port and the river delta – the most scenic part of the town – is particularly vulnerable and requires monitoring and protection. Further to the east, increased sediment supply to the tidal flat system in the Advent Valley may create difficulties for large ship operations near the town. The total assessment and accounting for coastal vulnerability and changing climate risks is still required. As the "Svalbard Project" and its instrument "Store Norske" are tied to exercising sovereignty through administration, research, education, and minor economic activities, the cost-effective maintenance of the infrastructure under climate change challenges set to be necessary for the community existence in the future (Hovelsrud et al., 2020; Ødegaard, 2022).

The public pathway emphasises the development of administration, research, and educational hubs. It is not capitalising on the benefits of the Arctic warming but is also not very vulnerable to its detrimental effects. Along this pathway, administrative functions and research activity are to be strengthened in the town (Misund, 2017). Furthermore, the region´s increasing militarisation influences civilian interests (Pedersen, 2019). The local climate perspective is needed to make adequate adjustments at minimal cost. It might look at approaches to integrate the Arctic town with its harsh but vulnerable Arctic climate; such an integration concept has become known as a "winter city" (Pressman, 1996). Weak place connections have complicated the integration due to short residence times; on average, dwellers stay for less than four years (Hovelsrud et al., 2020).

The critical challenges from the local climate perspective are snow avalanches and permafrost thaw in the eastern Longyearbyen areas. The local authorities have developed building codes and contingency plans, moved houses, and implemented zoning restrictions (see Fig. 3). The waterfront is a highly valued area with enhanced public attention to infrastructure development. In Longyearbyen, the coastal zone is also highly valued but underdeveloped. New buildings and walking routes are planned in this zone. At the same time, a coastal zone is where environmental changes impact the town's infrastructure the most. Significant ice content in frozen soils leads to local surface depressions, coastal erosion, and sliding (Jaskólski et al., 2018).

Conclusions

A local climate perspective refers to a viewpoint that focuses on understanding the specific climate conditions and patterns within a particular geographical area. In the Longyearbyen context, this perspective considers the unique features and characteristics of the local cold climate, including temperature variations, inversions, snow and permafrost features, sea ice patterns, and other environmental factors. Notably, a local climate perspective often considers the interactions between these features and their impact on the social, economic, and ecological aspects of the specific region or community under study. Longyearbyen is a place where the combination of local climate factors has a compound effect; temperature change, sea ice retreat, soil wetting, and permafrost thaw reinforce each other, sustaining local climate anomalies larger than anomalies found in the region. Our synthesis can be summarised by presenting the ranking of climate factors for each pathway, considering industrial, public, tourism, and conservation aspects (Fig. 4). The industrial pathway is sensitive to the dynamic climate factors that act on regional and local scales. The extent of the sea ice is the most critical factor here, as it determines the port´s accessibility. At seasonal time scales, the sea ice edge is controlled by the balance between Atlantic Waters penetration into Isfjorden and local circulation patterns. At longer, interannual time scales, it is factored by the hemispheric Arctic amplification processes and local physical feedback (Goosse et al., 2018; Previdi, Smith, & Polvani, 2021). Permafrost and snowpack stability, temperature, and precipitation changes are of lesser importance, as they could be tamed through technological solutions. However, more than traditional techno-fix solutions may be required if the local climate anomalies exceed certain thresholds, such as permafrost collapse (Winther & Gudmestad, 2023). Various measures to protect the infrastructure from damage include new buildings on steel pillars anchored in the underlying bedrock, avalanche barriers, and thermosyphons to stabilise permafrost. Permafrost is also protected by lifting facilities above the ground, reducing thermal radiation from the surface under buildings.

The public pathway is sensitive to geotechnical (infrastructural) safety factors in the settlement (Hjort et al., 2018). The immediate risks are related to permafrost and snowpack stability, which are factored in by local changes in temperature and precipitation. There is increasing awareness of this locality, manifested by setting geo-test sites and considering downscaling climate change projections (Instanes, 2016).

Is more sustainable acclimation of the town feasible? Hovelsrud et al. (2020) emphasise emerging adaptation dilemmas for Longyearbyen: climate change creates hazardous conditions with urgent safety planning measures, but “the strict environmental protection limits the action space.” Although physical climatology still undervalues the local climate perspective, it becomes clear that specific physical mechanisms in the Arctic can sustain large and significant local variations in the climate factors (Table 1). The Environmental Policy Act places environmental concerns above economic interests, and the Svalbard Act stipulates that the natural environment remains undeveloped (Hovelsrud et al., 2020). These stipulated policy restrictions call for a more spatially detailed climate assessment that might identify less vulnerable geographical areas for prospective development. We conclude that the local climate perspective has a considerable environmental impact and is indispensable for sustainable development at the local level. Hovelsrud et al. (2020) noted: “*Proactive adaptation includes adjustments in behavior and acceptance of increasingly adverse weather conditions.*”

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