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Research paper

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Climate-induced dynamics of ice cover in southeastern Greenland (2000–2024) revealed by satellite remote sensing

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Summary

This study investigates multidecadal changes in the extent of glacierized surfaces in Kommune Kujalleq, southeastern Greenland, between 2000 and 2024. Multispectral satellite imagery from Landsat 7 and Landsat 8, combined with climate data from MODIS and the Global Precipitation Measurement (GPM) mission, was used to quantify changes in summer ice cover and to evaluate their relationship with atmospheric drivers. The Normalized Difference Snow Index (NDSI ≥ 0.4) was applied to classify ice-covered pixels during the melt season (July–September), and climate variables were derived for both summer and winter seasons. The results reveal an overall net decline in ice-covered area of approximately 4% (about 1,600 km^2) over the 24-year period, with substantial interannual variability. Years such as 2015 and 2020 exhibited temporary increases in ice extent, coinciding with anomalously high snowfall and below-average summer temperatures, whereas significant losses occurred during warm and dry periods, notably in 2010 and 2024. Despite these fluctuations, the general trend remains one of retreat, driven primarily by sustained Arctic warming. The study highlights the effectiveness of remote sensing and cloud-based geospatial platforms for long-term cryospheric monitoring and contributes to a better understanding of regional glacier sensitivity to climatic variability in the context of global sea-level rise.

Keywords

remote sensing • Landsat • MODIS • NDSI • climate changes • Google Earth Engine

1. Introduction

The Arctic has warmed markedly faster than the global mean during recent decades, with a pattern of amplification that intensifies melt energy across high latitudes [Rantanen et al. 2022]. In Greenland, this climatic shift has accompanied a transition from near-equilibrium toward sustained mass loss, beginning in the 1990s. Satellite syntheses that combine altimetry, gravimetry and feature tracking indicate large and accelerating losses from the Greenland Ice Sheet, with contributions from both negative surface mass balance and dynamic discharge [Mouginot et al. 2019, Otosaka et al. 2023, ESA 2023]. Process studies show that strong melt seasons can produce stepwise lowering of the ablation zone, and that persistent changes in cloud cover can amplify surface energy available for melt [Bevis et al. 2019, Hofer et al. 2017]. Greenland runoff has also increased nonlinearly in response to recent warming, consistent with enhanced surface ablation [Trusel et al. 2018], not restricted only to coastal areas [IPCC 2023].

Southeast Greenland, which includes the municipality of Kommune Kujalleq, is a sensitive sector where many outlet glaciers terminate in the ocean and where snowfall is comparatively high. Historical and satellite mapping document multidecadal retreat of peripheral glaciers in this region, overprinted by shorter episodes of stillstand or readvance [Bjørk et al. 2012]. Recent analyses report synchronous retreat of many peripheral glaciers in southeast Greenland, linking regional behaviour to atmospheric forcing [Liu et al. 2022]. Dynamic studies further indicate that sustained frontal retreat can reduce back-stress and maintain thinning and drawdown, even when individual summers are cool or winters are snow-rich [King et al. 2020, Mankoff et al. 2020].

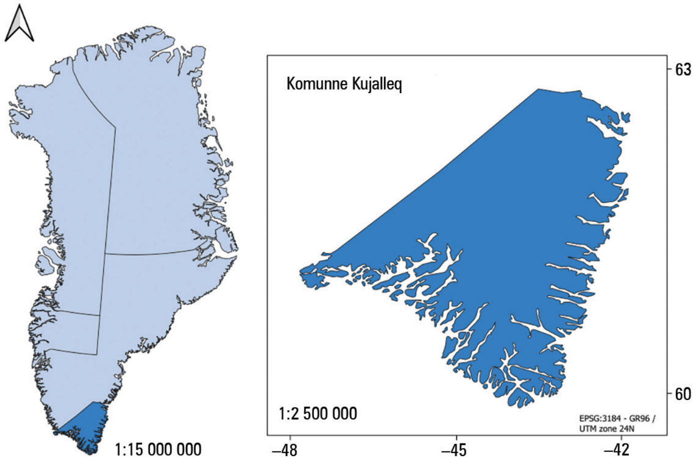
Despite this growing body of work, two related gaps remain for climatically dynamic sectors such as Kommune Kujalleq. First, there are comparatively few region-focused, area-based assessments that track summer ice extent at consistent spatial resolution across many years and that report uncertainties specific to data limitations in key periods (for example, Landsat-7 SLC-off). Second, links to climate are often made with coarse or annual diagnostics, whereas season-specific proxies for melt energy and accumulation can sharpen interpretation. For instance, land surface temperature from MODIS (LST) offers a spatial proxy for summer energy, and GPM precipitation can be partitioned into an accumulation season and a melt season window to approximate the balance between winter input and summer loss.

This study addresses these gaps by delivering a region-focused assessment of summer ice-covered area in Kommune Kujalleq from 2000 to 2024 using cloud-screened Landsat mosaics and a transparent optical classifier (NDSI with a threshold near 0.4). Climate context is defined with MODIS LST and GPM precipitation summarized over two seasonal cycles that distinguish winter accumulation from the main melt period. Consistency with established geospatial practice is maintained through export to a common CRS (WGS 84 / UTM 23N, EPSG: 32623), treatment of SLC-off years with explicit caution, and removal of LST outliers using bounds guided by regional climatology. The approach yields a comparable, area-based indicator that is sensitive to year to year anomalies but anchored to a multi decadal trajectory.

2. Data and methods

2.1. Area of study

Kommune Kujalleq, the southernmost municipality of Greenland, is located in the island's southeastern sector. The region is characterized by an Arctic climate moderated by maritime influence, with average mid-summer temperatures reaching approximately 7°C and mid-winter temperatures averaging –7°C in coastal zones [Rasmussen 2024]. Annual precipitation exceeds 1,500–1,900 mm in the southernmost areas, contributing to relatively high snow accumulation compared to central and northern Greenland. The municipality includes both peripheral glaciers and parts of the Greenland Ice Sheet margin. In 2000, ice cover accounted for approximately 73% of the region's land area (around 41,000 km²), making it a key indicator of cryospheric sensitivity to climate variability.



Source: Author's own study

Fig. 1. Study area

2.2. Data

This study employed multitemporal satellite datasets to assess changes in summer ice cover and associated climatic conditions. Landsat 7 ETM+ and Landsat 8 OLI provided multispectral imagery at 30 m spatial resolution for six target years: 2000, 2005, 2010, 2015, 2020, and 2024. MODIS Land Surface Temperature products (MOD11A2 and MYD11A2) were used to estimate near-surface air temperatures at ~1 km resolution, while precipitation estimates were derived from the Global Precipitation Measurement (GPM) mission with a nominal resolution of 10 km [Smith et al. 2007]. All remote sensing data were processed within the Google Earth Engine (GEE) platform [Gorelick et al. 2017]. The processed outputs, including seasonal mosaics and binary masks, were exported to QGIS 3.30 for spatial analysis and area calculations.

2.3. Methodology

The overall methodological workflow used for the image and precipitation data was presented on the diagram (Fig. 2).

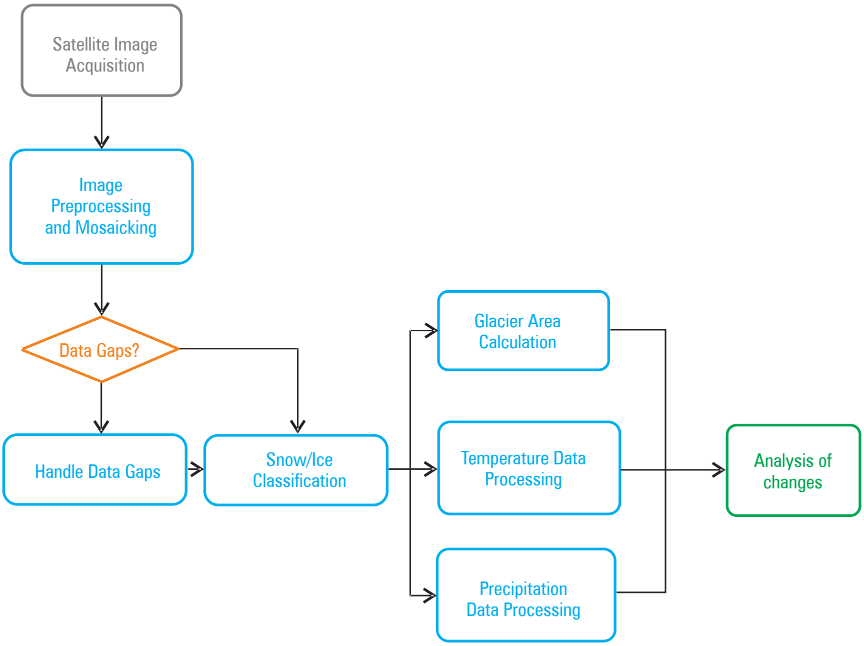


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Fig. 2. Diagram of the methodological workflow

Ice-covered area was mapped for each study year using composite mosaics of cloud-free Landsat images from July to September. Cloud masking was applied based on quality assessment bands, and median reflectance values were calculated per pixel to generate annual mosaics. For 2005 and 2010, Landsat 7 imagery was affected by the Scan Line Corrector (SLC) failure, resulting in data gaps. These years were treated with caution due to potential underestimation of ice extent [Storey et al. 2005].

Ice and snow were identified using the Normalized Difference Snow Index (NDSI), calculated from formula (1) [Gaur et al. 2022]:

$$NDSI = \frac{GREEN - SWIR}{GREEN + SWIR} \tag{1}$$

where:

GREEN – reflectance in the GREEN spectral band,
SWIR – reflectance in the SWIR spectral band.

A threshold of NDSI ≥ 0.4 was applied to classify pixels as snow/ice [Mishra et al. 2009, Gaur et al. 2022]. The resulting binary ice masks were exported to QGIS and intersected with the municipal boundary to compute ice-covered area in square kilometers and as a percentage of the total region.

Climate data were extracted for the same summer period. MODIS temperature values for July, August, and September were averaged to produce mean summer temperatures for each year (Table 1). To avoid outliers, values outside climatologically realistic bounds (e.g. –10°C to +15°C in July) were excluded [Jiang and Ye 2022]. GPM-derived precipitation was divided into two seasonal cycles (Table 2): the snow accumulation period (15 August – 31 May) and the summer melt period (1 June – 15 August), following Gallagher et al. [2022]. Precipitation totals for each cycle were converted to monthly averages (mm/month) to assess seasonal variability and its potential relationship with observed changes in ice extent.

Table 1. Average monthly temperatures in Kommune Kujalleq form MODIS data

Year	Month	Average temperature	Year	Month	Average temperature
2000	July	-0.26	2005	July	-0.45
	August	-0.66		August	-2.15
	September	-4.97		September	-5.66
2010	July	-0.37	2015	July	-0.73
	August	0.17		August	-0.82
	September	-4.62		September	-5.18
2020	July	-0.5	2024	July	-1.02
	August	0.14		August	-0.1
	September	-6.52		September	-2.96
Average		July		**-0.56**	
		August		**-0.57**	
		September		**-4.99**	

Table 2. Average monthly precipitation value in Kommune Kujalleq [mm/month]

Year	Cycle	Precipitation value [mm/month]
2000	First (15.08.1999–30.05.2000)	83.91
	Second (01.06.2000–15.08.2000)	48.74
2005	First (15.08.2004–30.05.2005)	91.58
	Second (01.06.2005–15.08.2005)	117.51

Table 2. cont.

Year	Cycle	Precipitation value [mm/month]
2010	First (15.08.2009–30.05.2010)	57.38
	Second (01.06.2010–15.08.2010)	97.61
2015	First (15.08.2014–30.05.2015)	99.21
	Second (01.06.2015–15.08.2015)	65.61
2020	First (15.08.2019–30.05.2020)	85.18
	Second (01.06.2020–15.08.2020)	95.88
2024	First (15.08.2023–30.05.2024)	94.43
	Second (01.06.2024–15.08.2024)	data not available

3. Results and discussion

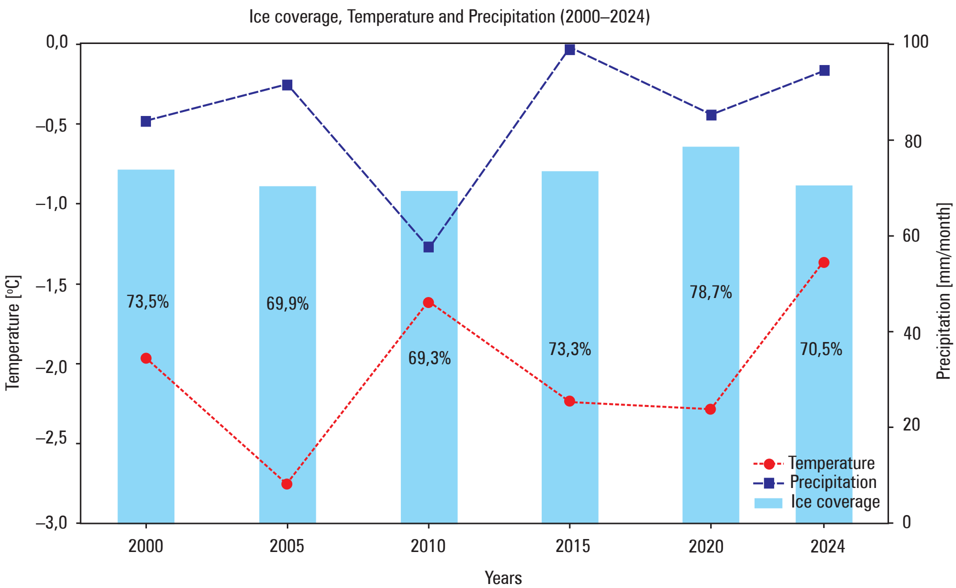
Results are reported as both the area fraction and the change relative to 2000, with climate context provided by mean summer LST and accumulation season precipitation. Ice extent across Kommune Kujalleq exhibited considerable variability between 2000 and 2024 (Table 3, Fig. 3). In the year 2000, the ice-covered area was approximately 41,000 km², equivalent to 73.5% of the municipality. By 2005, this had declined to around 39,000 km² (69.9%), although the accuracy of this estimate was compromised by the Landsat 7 scan line corrector (SLC) failure. In 2010, the ice extent further decreased to 38,500 km² (69.3%), corresponding to one of the warmest summers on record and the lowest recorded winter snowfall (57 mm/month).

A temporary change in trend occurred in 2015, with the ice extent increasing to 40,900 km² (73.3%), attributed to above-average winter precipitation (99 mm/month) and cooler summer temperatures (~–2.2°C). The most pronounced increase was observed in 2020, when the ice extent peaked at approximately 43,800 km² (78.7%). This anomaly coincided with exceptionally cold summer temperatures (~–2.3°C) and high winter snowfall (~85 mm/month), underscoring the sensitivity of the ice cover to short-term climatic variability.

By 2024, ice extent had again declined to approximately 40,000 km² (70.5%). Despite above-average winter precipitation (~94 mm/month), the summer of 2024 recorded the highest mean temperature in the study period (–1.3°C), which contributed to significant melt. Overall, ice extent decreased by approximately 1,600 km² (–4%) between 2000 and 2024.

Table 3. Area of ice cap in percentage with average monthly temperature and precipitation in the first cycle in Kommune Kujalleq

Year	Extent of ice cap [%]	Average temperature [°C]	Average precipitation [mm/month]
2000	73.5	-1.96	83.91
2005	69.9	-2.75	91.58
2010	69.3	-1.61	57.38
2015	73.3	-2.24	99.21
2020	78.7	-2.29	85.18
2024	70.5	-1.36	94.43



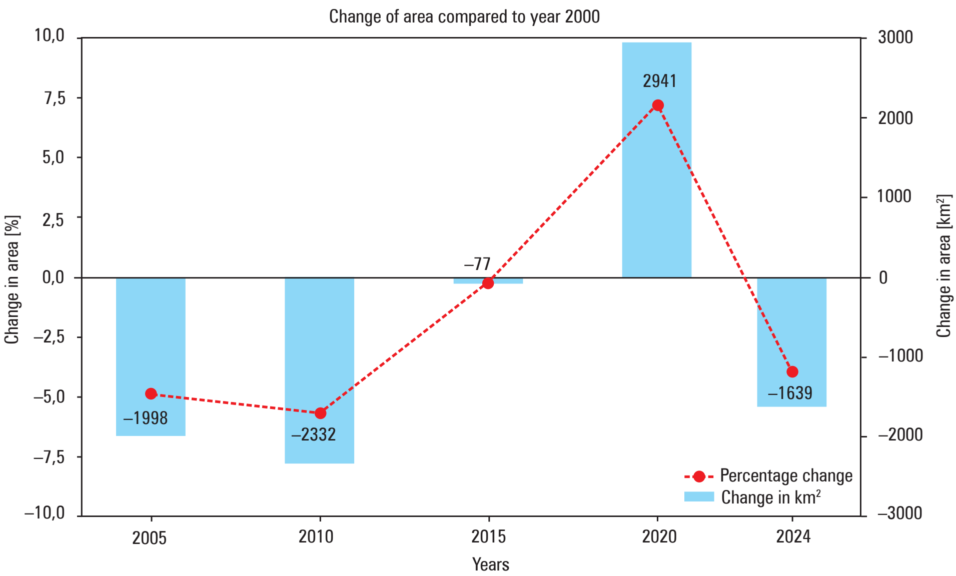
Source: Author's own study

Fig. 3. Graph of extent of ice cap, average temperature and precipitation between 2000 and 2024

Changes in ice extent relative to the year 2000 further emphasize the nonlinear nature of ice loss. The most significant relative decline occurred in 2010 (–5.7%), followed by 2024 (–4.0%). The only net gain was recorded in 2020 (+7.2%). While short-term fluctuations were evident, the overall trend supports sustained retreat driven by long-term atmospheric warming.

Table 4. Changes in the area covered by the ice sheet in Kommune Kujalleq between the reference year 2000 and later periods

Year	Change in area compared to 2000 [km²]	Change in area compared to 2000 [%]
2005	-1998	-4.9
2010	-2332	-5.7
2015	-77	-0.2
2020	2941	7.2
2024	-1639	-4.0



Source: Author's own study

Fig. 4. Graph of changes in the area covered by the ice sheet in Kommune Kujalleq between the reference year 2000 and later periods

These results align with previous studies highlighting the dynamic response of Greenland's peripheral glaciers to climatic drivers [Bjørk et al. 2012, Liu et al. 2022]. The periods of ice sheet growth were associated with increased snow accumulation and cooler summers, while the years of glacier retreat were associated with higher temperatures during the melting season and reduced snowfall. The findings emphasize the critical role of interannual climate anomalies in modulating short-term glacier behavior within a broader trajectory of climatic decline.

Uncertainties in the analysis stem primarily from the spatial gaps in Landsat 7 data (especially in 2005 and 2010), potential misclassification of late-lying snow as glacial ice, and the absence of ice thickness data. Future studies integrating elevation change data from altimetry missions (e.g., ICESat-2) and applying annual temporal resolution are recommended to capture transient events more accurately and to link surface area change with volume loss.

At the scale of southeast Greenland, the pattern documented here aligns with evidence that long-term mass loss is dominated by surface mass balance deficits, while discharge from marine terminating outlets modulates year to year area. Multidecadal syntheses show accelerating mass loss since the 1990s and persistent retreat of glacier fronts in this sector [Mouginot et al. 2019, Otosaka et al. 2023, Bjørk et al. 2012, Liu et al. 2022]. Satellite based discharge time series and frontal change inventories indicate that sustained frontal retreat can trigger positive feedbacks, such as loss of resistive stresses and thinning, that maintain dynamic drawdown even when single years are cool or snow rich [King et al. 2020, Mankoff et al. 2020]. Within this framework, the increases in 2015 and 2020 are interpreted as short lived responses to cooler summers and stronger winter accumulation rather than a reversal of the multidecadal trajectory; the NOAA Arctic Report Card documents 2020 as a year with widespread anomalous cold over southern Greenland [Moon et al. 2020].

Climatic mechanisms diagnosed elsewhere help explain the interannual variability observed in Kommune Kujalleq. Episodes of reduced summer cloud cover and anticyclonic blocking enhance shortwave radiation at the surface and promote melt, particularly along the peripheral ice and low elevation margins [Hofer et al. 2017]. Basin scale analyses further show that the sensitivity of the surface mass balance to summer temperature has increased in recent decades, and that strong melt years can produce stepwise lowering of the ablation zone that is not immediately compensated by subsequent snowfall [Bevis et al. 2019]. Regional climate modelling of the surface mass balance for Greenland indicates that the combined effect of warm summers and modest winter accumulation produces persistent deficits [Noël et al. 2018]. Consistency between those results and the present area-based indicators strengthens the interpretation that 2000–2024 was characterized by a net retreat modulated by short-term anomalies; integrating ICESat-2 height change tracks and discharge records for the main outlets in this sector would allow the relative roles of dynamics and surface forcing to be quantified [Mankoff et al. 2020].

4. Summary and conclusions

This study analyzed temporal changes in ice cover within Kommune Kujalleq, southeastern Greenland, using satellite remote sensing data from 2000 to 2024. Landsat imagery, MODIS land surface temperature records, and GPM precipitation estimates were integrated to map summer ice extent and assess its relationship with climatic variables. The results revealed an overall decrease of approximately 4% in ice-covered areas during the 24-year period, with significant interannual variability. Temporary increases in ice extent were observed in 2015 and 2020, both associated with above-average winter snowfall and cooler summer temperatures. Conversely, substantial reductions in ice area occurred in 2010 and 2024, coinciding with higher melt-season temperatures and reduced or ineffective winter accumulation. Despite these fluctuations, the overarching trend indicates a progressive retreat of ice cover in response to long-term regional warming. The findings underscore the strong climatic sensitivity of southeastern Greenland's glacierized landscape and the importance of sustained monitoring. While surface area provides a valuable indicator of change, it does not capture underlying changes in ice volume. Thus, future research should incorporate altimetric and gravimetric data to assess mass balance and vertical thinning.

Continued integration of high-resolution satellite data and seasonal climate records is essential for understanding the evolving dynamics of Greenland's ice cover and its implications for sea-level rise. These efforts will support more accurate forecasting of cryospheric change and contribute to the global climate adaptation strategy.

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