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Spatial and temporal patterns of land surface temperature in Greenland from 2000-2019

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सार – ग्रीनलैंड द्वीप में पारिस्थितिक घटनाओं को आकार देने में तापमान गतिकी एक महत्वपूर्ण कारक है। विभिन्न क्षेत्रों में पारिस्थितिक गतिकी को समझने के लिए सतह तापमान (एलएसटी) प्रतिरूप की जाँच करना महत्वपूर्ण है। ग्रीनलैंड की बर्फ की चादर के और अधिक पिघलने से समुद्री और स्थलीय पारिस्थितिकी प्रणाली नष्ट हो सकती है। इस अध्ययन में पूरे द्वीप पर मौसमी प्रतिरूप और एलएसटी प्रतिरूप को समझने के लिए मॉडरेट रेजोल्यूशन इमेजिंग स्पेक्ट्रो रेडियोमीटर उपग्रहों के डेटा का उपयोग किया गया। 2000 और 2019 के बीच की अवधि पर ध्यान केंद्रित करते हुए, इस अध्ययन ने सभी उपखंडों के लिए मौसमी प्रतिरूप की पहचान करने के लिए एक प्राकृतिक क्यूबिक स्पलाइन मॉडल का उपयोग किया। डेटा को मौसमी रूप से समायोजित किया गया और दूसरे क्रम के ऑटोसहसंबंध घटक के साथ फ़िल्टर किया गया। एलएसटी प्रतिरूप की पहचान करने के लिए स्पलाइन को फिर से फिट किया गया और फिर स्थानिक सहसंबंध को समायोजित करने के लिए एक बहुचर समाश्रयण मॉडल का उपयोग किया गया। हम एक उदाहरण से स्पष्ट करते हैं कि ग्रीनलैंड की अधिकांश सतह तापमान की प्रवृत्ति स्थिर है। अध्ययन अवधि के दौरान ग्रीनलैंड में एलएसटी में देखे गए ये प्रतिरूप बताते हैं कि पिछले दो दशकों के भीतर ग्रीनलैंड में देखी गई बर्फ की चादर का पिघलने का कारण जरूरी नहीं कि एलएसटी प्रतिरूप हो यह अन्य कारकों के कारण भी हो सकता है।

ABSTRACT. Temperature dynamics on the island of Greenland are an important factor in shaping ecological events. Investigating the land surface temperature (LST) patterns is critical for understanding ecological dynamics across different regions. Further melting of the Greenland ice sheet could deva state marine and terrestrial ecosystems. This study used data from Moderate Resolution Imaging Spectroradiometer satellites to understand the seasonal patterns and patterns of LST over the entire island. Focusing on the period between 2000 and 2019, this study used a natural cubic spline model to identify seasonal patterns for all sub-regions. The data were seasonally adjusted and filtered with a second-order autocorrelation component. The spline was fitted again to identify the LST pattern, and a multivariate regression model was then used to adjust for spatial correlation. We illustrate that most of the land surface of Greenland hasstable temperature trends. These observed patterns in LST in Greenland during the study period suggest that the observed ice-sheet melting in Greenland within the last two decades could be due to other factors, not necessarily LST patterns.

Key words – Land surface temperature, Cubic spline, Multivariate regression, Seasonal patterns, Greenland.

1. Introduction

The land surface temperature (LST) is an important parameter when considering the exchange of heat and energy on Earth. Globally, LST has become an integral part of human existence; affecting every sphere of life (Schlenker and Roberts, 2009; Xu *et al.*, 2015). The changes in LST, especially in the Arctic region, affect different ecosystems and their functions (Post *et al*., 2009; Daanen, 2011). Over the past century, the average land and ocean surface temperaturehas increased by about 0.85 [0.65 to 1.06] °C, significantly due to natural and human activities, with corresponding consistent rise in the global mean sea level (approximately 19 cm increase from 1901 to 2010) (IPCC, 2013). A large portion of the increase has been attributed to global warming. About 75% of the increase in the ocean's volume is due to thermal expansion of water and the melting of glaciers and ice sheets since 1971(Church *et al*., 2013). Over the last few decades, there has been universal attention to global warming and more research has focused on melting ice sheets near Greenland and Antarctica. Some studies have suggested that the proportion of global sea-level rise due to melting glaciers and ice sheets could be between 19%-40% (Church *et al*., 2013; Cazenave *et al*., 2009; Helm, 2014).

There is evidence of accelerated warming of the Arctic region, with the rate of melting of the Greenland ice sheet increasing between 1990 and 2005, partly due to surface water runoff (Hanna *et al*., 2008; Rignot *et al*., 2011; Van den Broeke, 2009). Meteorological stations on the ice sheet have low density, making it challenging to obtain the surface temperature over the entire ice sheet (Hall *et al*., 2013). Amidst such difficulty, satellites provide LST measurements of ice sheets at high resolutions and with extensive coverage. For instance, the Moderate Resolution Imaging Spectroradiometer (MODIS) has become a reliable source for satellite-based data on LST (Wan *et al*., 2004). Different studies have analyzed data from MODIS describe temperature trends in different regions of the world. (Hughes *et al.*, 2006; Dong *et al*., 2015; Me-ead and McNeil, 2016). In the analysis of temperature data, methods such as remote sensing algorithms, simulation models and other statistical methods have been applied to data from different regions (Hughes *et al*., 2006; Dong *et al*., 2015; Me-ead and McNeil, 2016). Other research has employed polynomial regression models (Wanishsakpong and McNeil, 2016; Wongsai *et al*., 2017; Sharma *et al*., 2018) and natural cubic splines (Chylek *et al*., 2006) to investigate the patterns and trends in LST.

Several studies have been conducted with satellite temperature data on Greenland, and these have reported warming trends, especially during the latter decades of the 20^{th} century (Chylek *et al*., 2006; Tedesco *et al*., 2016). However, according to MODIS data, recent temperature trends over the whole island (2001-2015) are inconsistent over wide areas; most areas are cooling while some ice-free parts are warming (Westergaard *et al*., 2018). Greenland remains an important region in climate science as the melting of ice sheets has a direct impact on sea levels. As a result of these contrasting findings, this study aims to describe the seasonal patterns and patterns of LST using high-resolution data from MODIS at different regions across Greenland.

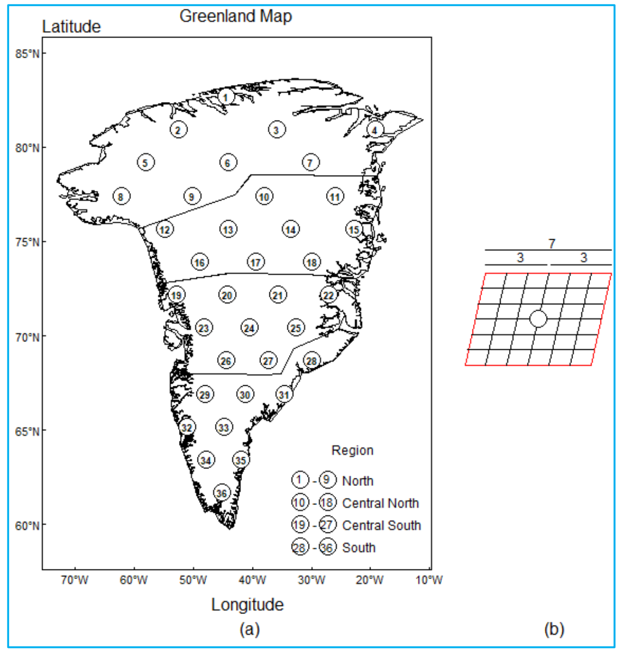

Fig. 1. Greenland Map, (a) showing the 36 sub-regions of the study, (b) sub-regions dimension

2. Materials and methods

2.1. *Study areas and data management*

Greenland is the world's largest island. This study divided Greenland island into 4 regions, with each region consisting of 9 sub-regions Fig. 1(a). The classification into sub-regions helps to determine LST variability, even across small areas. There were 36 sub-regions. The LST sub-region has a 3×3 -kilometer (km) dimension, encompassing from the center location as shown in Fig. 1(b). Each sub-region had an area of 7×7 km^2 with 49 pixels. The sub-regions were classified as either ice-free or ice-covered.Sub-regions 1, 4, 15, 19, 22, 28, 31, 32, 35 and 36 were ice-free. The four larger regions, namely North, Central-North, Central-South and South with 9 sub-regions within each region as shown in Fig. 1(a).

MODIS sensors are carried by both the Terra and Aqua satellites. Terra was launched two years before Aqua, with the first observations in 2000. Early versions of the MODIS Aqua snow products were produced differently than their Terra counterparts due to Band 6 detector issues on Aqua shortly after launch (Nation Snow and Ice Data Center, 2023). Therefore, the land surface temperature data in this study was obtained from the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature/Emissivity 8-day, MOD11A2, product (https://modis.ornl.gov/globalsubset/)

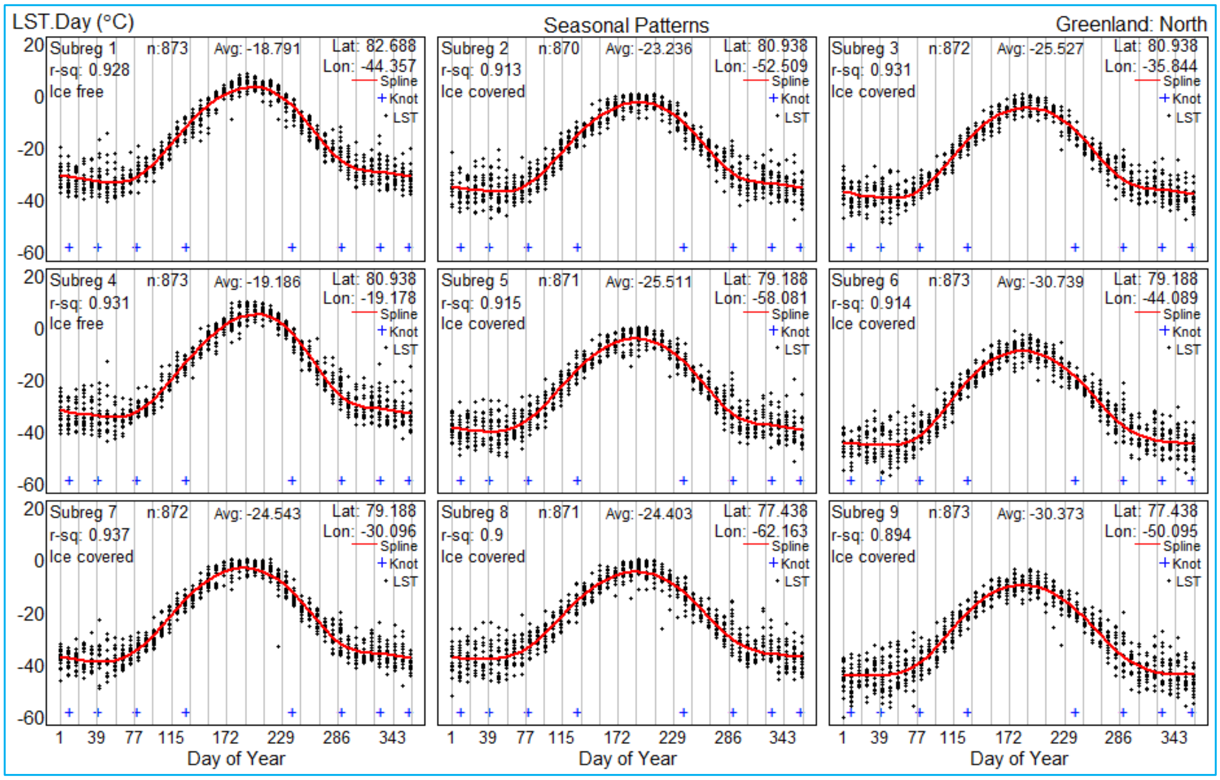

Fig. 2. Seasonal pattern in North Greenland

The data provided average temperatures every 8-days per-pixel of clear sky conditions with a 1km spatial resolution in a 1,200 by 1,200 km grid. Validation of land-surface temperatures obtained from MODIS has shown consistency with *in-situ* LST on the Greenland ice sheet. LST has a bias over the Greenland ice sheet which mainly occurs in winter (Yu *et al*., 2022). The estimated LST in the northwest, northeast, and central parts have higher accuracy (Yu *et al*., 2022). However, many studies validating the LST from MODIS have confirmed that the MOD11 LST data agrees well with ground measurements over densely vegetated areas, snow/ice cover, and inland water surfaces (Wan *et al*., 2003; Wang *et al*., 2014; Li *et al*., 2017). Therefore, MODIS can demonstrate temporal and spatial variability of LST with reasonable accuracy (Yu *et al*., 2022).

Data was recorded every 8 days from March 2000 to February 2019. To reduce spatial correlation within each sub-region (Sharma *et al*., 2018), the average of the 8-day LST for the 49 pixels was used. Each complete year consisted of approximately 46 observations for each sub-region. Therefore, a total of 874 observations were recorded for each sub-region over the study period (a total of 31,464 observations were obtained overall sub-region). However, 165 (0.52%) of the total observations were missing.

2.2. *Statistical methods*

A natural cubic spline function with 8 knots was used to smooth the data and to identify seasonal patterns in all sub-regions. Knots are placed at several places within the data range to identify the points where adjacent functional pieces join. The cubic spline function is given by equation (1).

$$S_t = a + bt + \sum_{k=1}^{p} C_k \left(t - t_k\right)^3 + \tag{1}$$

Where s is the spline function, a, b and C_k are constants, t represent time and $t_1 < t_2 < \cdots < t_p$ are specified knots. Seasonal adjustment of the data was done by subtracting the fitted values from the cubic spline function and then adding the average temperature for each sub-region. The seasonal adjustment equation is shown in equation (2).

$$y_t = x_t - \hat{s}_t + \bar{x} \tag{2}$$

Where y is the seasonal adjusted LST, x_t are the observed values at time t, $\hat{s}$ is the fitted value from the natural cubic spline model, and $\bar{x}$ represents the overall mean. An autoregressive moving average, ARIMA (2,0,0)

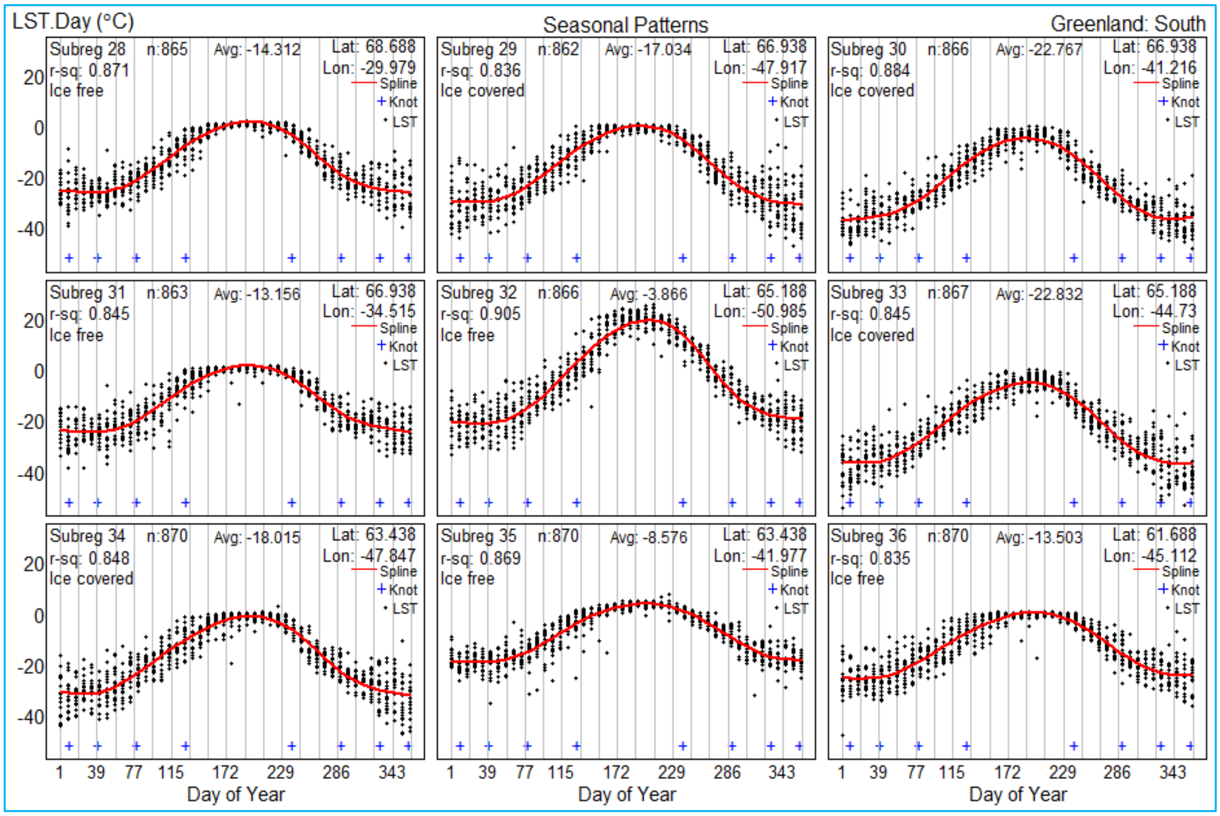

Fig. 3. Seasonal pattern in South Greenland

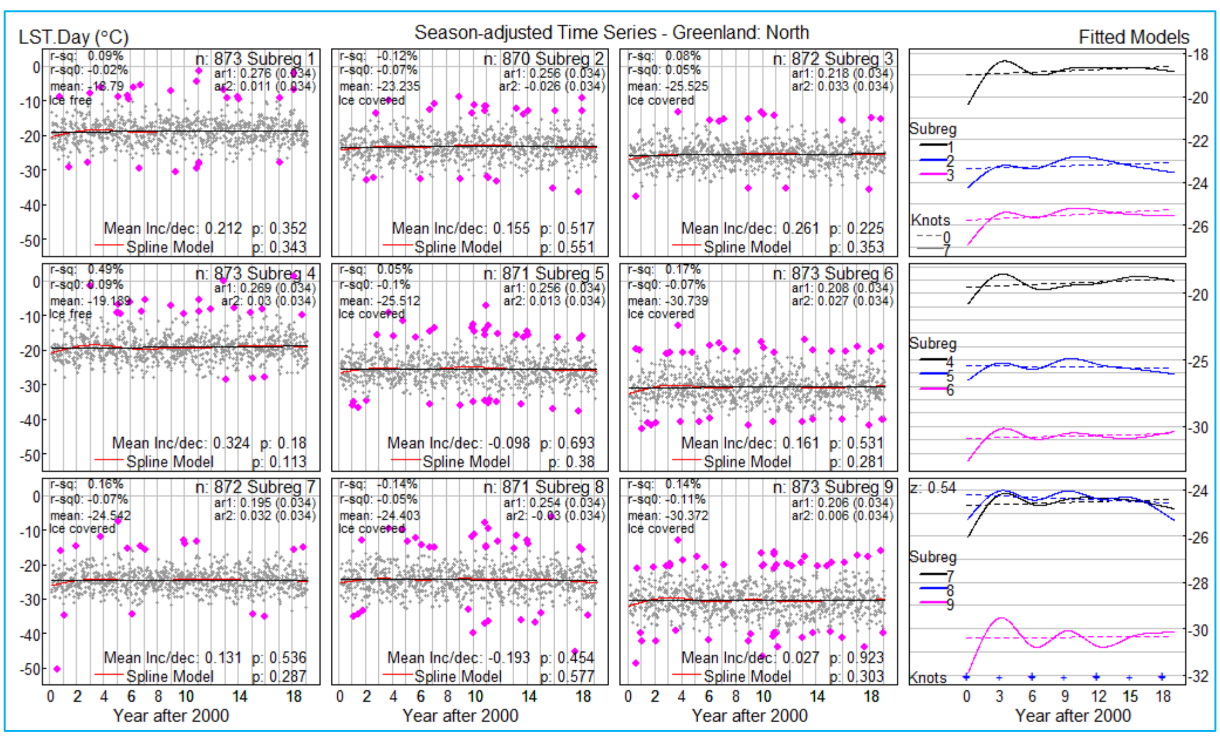

Fig. 4. Seasonally adjusted LST in the North region of Greenland. The magenta dots are outlying temperature observations for each sub-region

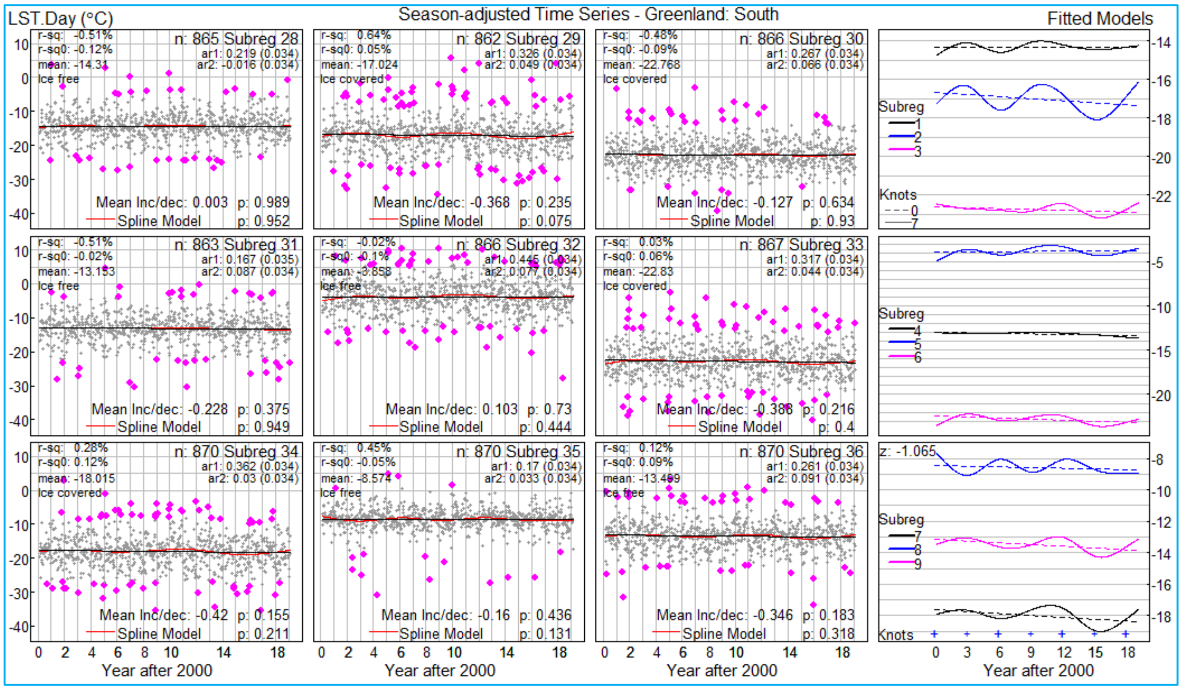

Fig. 5. Seasonally adjusted LST in the South region of Greenland. The magenta dots are outlying temperature observations for each sub-region

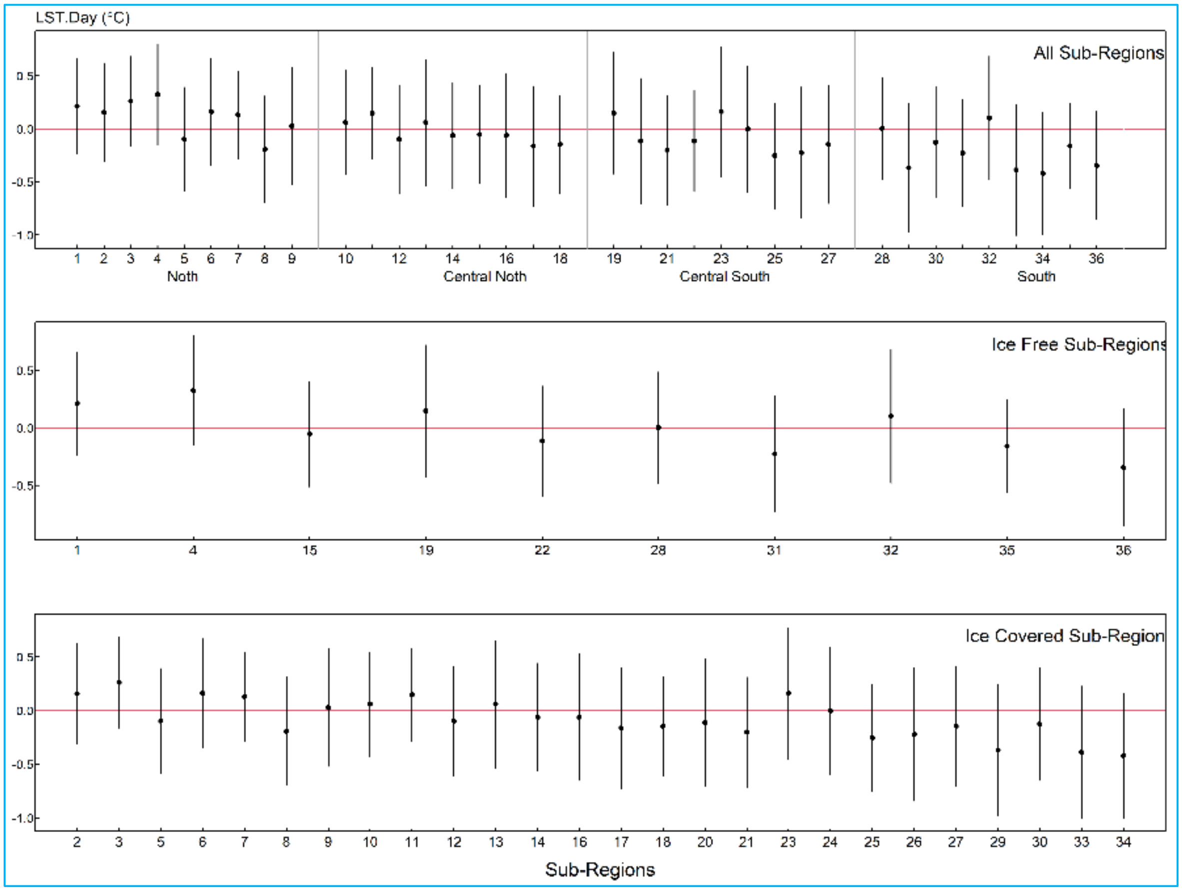

Fig. 6. 95% confidence intervalsof land surface temperatures changeat various sub-regions for all (top), ice-free (middle) and ice-covered (bottom) sub-regions of Greenland

model was used to reduce autocorrelation between the seasonally adjusted data.

After seasonal adjustment and removal of autocorrelation, the spline model was fitted again with 7 knots to identify the LST patterns for each sub-region and a simple linear regression model was used to estimate the mean temperature increase per decade at each sub-region. However, the spline model could not account for all spatial correlation in the data. Hence, a multivariate regression model was used because it can handle spatially correlated data. R was used to analyze the data (R Core Team, 2020).

3. Results

The North (sub-region 1 to 9) and South (sub-region 28 to 36) regions of Greenland were used to present the results. The North region had two ice-free sub-regions, while the South region had five. Fig. 2 (North) and Fig. 3 (South) regions, exhibited slight variation in the temperature patterns for all sub-regions. In the figures, the red curves represent natural cubic splines with 8 knots. The LST patterns were consistent with the seasons of Greenland.

Temperature increments are observed from the start of spring (day 60) through to mid-summer. Maximum temperatures were observed in the mid-summer (between 180 and 200). After day 200, the temperature patterns in each panel begin to decline. The continues throughout the autumn and temperatures reach a peak minimum level in winter (days 330 to 60). These patterns were consistent for all regions, although the peak levels were quite different. The peak levels were height sub-region with ice free. Also, the ice-free sub-regions had higher average LST compared to the ice-covered sub-regions, with temperatures ranging from -19.186 °C (sub-region 4) to -3.866 °C (sub-region 32). The seasonally-adjusted LST for the North and South regions are shown in Figs. 4&5, respectively. The panels on the right represent the results from the spline function with 7 knots and the simple linear regression model.

The spline model with 7 knots revealed similar cyclic patterns for each sub-region. The p-values from the model for each sub-region were all higher than 0.05. The peak was observed around 2003 in the North and South regions, except sub-regions 30, 31 and 35 in the North, which were dropped. Most mean increases per decade for the North region were positive. In contrast, the highest increases per decade for the South region were negative. The 95% confidence intervals for each sub-region's mean increase per decade are illustrated in Fig. 6. The figure indicated no differences between the LST changes

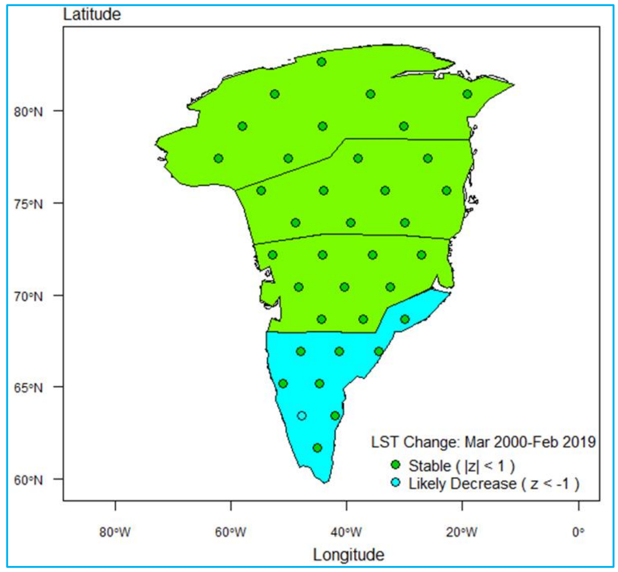

Fig. 7. Land surface temperature changes in each region of Greenland

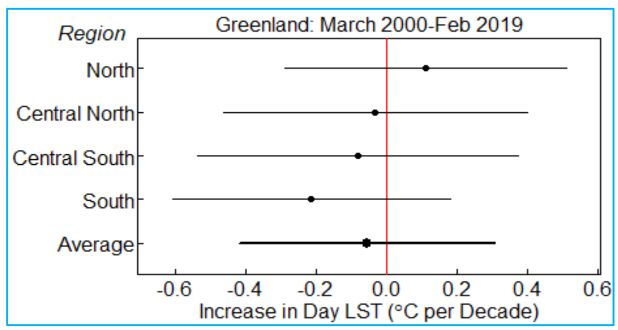

Fig. 8. 95% Confidence interval of temperature change across Greenland

between ice-free and ice-covered sub-regions. The LST changes in each region were estimated with a multivariate regression model.

The multivariate regression model showed that temperature patterns in the North, Central-North, and Central-South were stable over the study period, while the pattern in the South likely decreased, as shown in Fig. 7.

The means and 95% confidence intervals for the temperature increase per decade across the four regions of Greenland and overall from March 2000 to February 2019 are shown in Fig. 8. The average temperature increase for the whole island was -0.055 °C (95% CI: -0.418, 0.307). Each confidence interval includes zero, which indicates a non-significant change in LST.

4. Discussion and conclusion

We analyzed and surface temperatures over Greenland using satellite data from MODIS. We used a natural cubic spline model and multivariate regression to describe LST from 2000 to 2019. The cubic spline was able to detect annual seasonal patterns in LST. According to Wongsai *et al*. (2017), the natural cubic spline function is able to extract seasonality even when there are substantial missing values in the data. The spline function has also been applied to similar MODIS data from other regions to explain the seasonal patterns in climate data (Wanishsakpong and McNeil, 2016; Chen *et al*., 2006).

The observed seasonal pattern in LST indicates that the ice-free sub-regions of Greenland are warmer than the ice-covered sub-regions. LST peaked during mid-year (summer) and decreased in winter. The relatively warm temperature observed over the ice-free sub-regions, especially during the summer, is attributed to population density (Westergaard *et al*., 2018). All 36 sub-regions in this study had similar temperature patterns over the study period.

Moreover, the spline function with 7 knots showed seasonally adjusted LST patterns, which could be attributed to the placement of the knots. The linear regression model was used to observe changes in LST for each sub-region. However, all *p*-values were greater than 0.05, suggesting that the LST from different sub-regions were not statistically different in terms of temperature change. This study showed that the LST over Greenland was mostly stable across ice-free and ice-covered regions. This finding is consistent with a study by Hanna *et al*. (2021), which found short-term warming and cooling between 2001 and 2019, with no significant overall temperature change across coastal stations, mainly ice-free with two ice-covered stations. However, from 1991 to 2019, significant warming was observed in winter, spring and summer (Hanna *et al*., 2021). Warming trends observed across ice-free Greenland from 1986 to 2016 are mainly related to warming in the 1990s. The recent and detailed MODIS LST trends during 2001 and 2015, show contrasting trends across Greenland, with a cooling trend. The ice-free parts of Greenland showed a slight drop in temperatures with fluctuations from year to year (Westergaard *et al*., 2018).

The findings from this study also indicated that the LST in each sub-region had no significant difference in temperature change due to the different properties of ice and land. Therefore, each of the nine sub-regions were combined into four main regions, revealing that three (North, Central North, and Central South regions) were stable regarding LST. However, the South region had trends that were likely to decrease.

Different studies have analyzed data from different periods. In comparison, each period showed a contrasting trend of LST change. Over the last decade, warming over Greenland has slowed down (IMBIE, 2020; Hanna *et al*., 2020; Khazendar *et al*., 2019). In coastal southern Greenland, the temperature during 1958-2001 showed a significant cooling (Hanna *et al*., 2020).A recent study by Matsumura *et al*., (2021) reporting a slowdown of warming in Greenland suggested that the Central Pacific El Niño Southern Oscillation teleconnection plays a key role in recent summer Arctic climate change. Climate scientists appear to be justified in raising their concerns about the decrease in ice in Greenland. The findings from this study present no evidence of warming over ice-free and ice-covered areas. A major limitation in using MODIS data is that MODIS is an optical sensor, which has inherent limitations in observing sea ice and snow. Unlike a passive-microwave sensor, which can detect microwave energy through clouds, MODIS cannot observe the surface when cloud cover is present.

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