New Insights in Regional Climate Change: Coupled Land Albedo Change Estimation in Greenland from 1981 to 2017

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Abstract: Land albedo is an essential variable in land surface energy balance and climate change. Within regional land, albedo has been altered in Greenland as ice melts and runoff increases in response to global warming against the period of the pre-industrial revolution. The assessment of spatiotemporal variation in albedo is a prerequisite for accurate prediction of ice sheet loss and future climate change, as well as crucial prior knowledge for improving current climate models. In our study, we employed the satellite data product from the global land surface satellite (GLASS) project to obtain the spatiotemporal variation of albedo from 1981 to 2017 using the non-parameter-based M-K (Mann-Kendall) method. It was found that the albedo generally showed a decreasing trend in the past 37 years (~0.013 ± 0.001 decade⁻¹, p<0.01); in particular, the albedo showed a significant increasing trend in the middle part of the study area but a decreasing trend in the coastal area. The interannual and seasonal variations of albedo showed strong spatial-temporal heterogeneity. Additionally, based on natural and anthropogenic factors, in order to further reveal the potential effects of spatiotemporal variation of albedo on the regional climate, we coupled climate model data with observed data documented by satellite and adopted a conceptual experiment for detections and attributions analysis. Our results showed that both the greenhouse gas forcing and aerosol forcing induced by anthropogenic activities in the past 37 decades were likely to be the main contributors (46.1%) to the decrease of albedo in Greenland. Here, we indicated that overall, Greenland might exhibit a local warming effect based on our study. Albedo–ice melting feedback is strongly associated with local temperature changes in Greenland. Therefore, this study provides a potential pathway to understanding climate change on a regional scale based on the coupled dataset.

Keywords: Greenland; albedo change; ice-snow; Coupled Model Intercomparison Project 5 (CMIP5); detections and attributions (D&A)

1. Introduction

The Arctic climate has always been a hot issue and mirrors global climate change [1,2]. In recent years, with the rising of the global temperature, land and sea ice cover in the Arctic have decreased since the late 1970s and the trend is expected to increase due to a changing climate resulted from anthropogenic activities, which greatly threatens the development of coastal cities and the safety of life and property of people. At the same time, the melting of land and sea ice in the Arctic will also play an important role in global climate change [3], and affect the potential loss of the earth’s ecosystem functions in the future. Because most of the land is mainly distributed in the
northern hemisphere, the climate of the northern hemisphere in the middle and high latitudes has changed significantly in recent years [4–6]. Some studies have suggested that the melting of land and sea ice in the Arctic had changed the amount and spatial distribution of precipitation of arid and semi-arid regions in the middle and high latitude of the Northern Hemisphere [2,7,8]. Greenland is the largest land-based frozen water body in the Arctic zone. In recent years, the melting period of Greenland’s ice sheet occurred ahead of schedule in practice [7,9]. A great number of coupled Earth climate model results showed that Greenland’s ice was likely to speed up the melting rate under the current emission scenarios even if the emission stayed at an unchanged status, and its melting rate had been much faster than expected (Figure.1)[9]. Therefore, the study of the ice sheet and global climate change in Greenland has been a hot and controversial topic in recent years [10,11], although the study of climate change is quite complex because it is full of more uncertainties. Previous studies have found that ice melted at a high rate in Greenland, resulting in an increase in regional surface runoff and a decrease in observed surface albedo [12,13]. The change of albedo would affect the balance of surface energy and further affect the surface evapotranspiration, regional precipitation, and global atmospheric circulation [14–16].

Surface albedo is the ratio of surface solar radiation reflected and incident solar radiation, and it is an important parameter of global and regional climate change [15–17]. In Greenland, the effect of albedo on climate is mainly through ice-albedo climate feedback, and this feedback feature is particularly significant in high latitudes [13,18,19]. Some points are always expected to be addressed including that ice and snow have a high albedo and are typical ground objects with low net radiation energy. The melting of ice and snow will reduce the albedo, and the decrease of albedo will, in turn, lead to the increase of net radiation energy of the land surface, and then cause the increase of the local temperature in proximity of the land surface, further intensifying the melting of ice and snow and forming a positive feedback mechanism [8,12,15,20]. In addition, it has been found that in the ablation area (southwest and west Greenland), a large number of blisters and lakes had formed due to the melting of ice [11,12].

Satellite-based observation has laid a ground foundation for the study of global climate change. It has the characteristics of large area coverage and short revisit cycle, which effectively elevates the current understanding of global land albedo changes. In terrestrial ecosystems, global vegetation has increased by 7.1% in the past 35 years. The low albedo (high net radiation income), as well as high photosynthetic efficiency, which is characteristic of vegetation, promotes the primary intake of energy in the Earth’s ecosystem [20,21]; on the contrary, the high reflectance spectral characteristic of ice and snow makes it greatly weaken the energy income in the Earth’s system. Further, we should also highlight the difference between local cooling surrounding a soil induced by decreasing of albedo coefficient and heating which should occur in neighboring air layers where increasing heat fluxes occur due to increasing of ground reflected solar radiation [22]. If forests (including tropical rainforests) in low and middle latitudes play a large role in the adjustment of global change, the effect of ice-albedo on climate is also of concern in high latitudes, especially in areas covered by ice and snow for many years above bare ground in high latitudes zones [14,15]. Generally, GRACE (Gravity Recovery And Climate Experiment) data have been used for assessing ice mass balance in Greenland and most of Antarctica [7,23]. Numerous studies (radar detection of ice layers and ice-core sampling) have confirmed that melting has begun to occur in areas of low elevation in Greenland, such as in melt regions (northeast and northwest, mostly south)[12]. For now, although the research of both inter-annual and seasonal variability in ice is mostly based on GRACE data and reanalysis dataset, GRACE data, having a short time scale and station-based observations, are mostly limited. In addition, multi-pattern climate models provide a large number of climate simulation scenarios and also facilitate our understanding of ice sheet melting [4,24]. However, regarding the role of ice-albedo feedback mechanisms in the polar climate zone, to date, indeed, we still lack an understanding of the changes in regional albedo in Greenland from the long time-series. Therefore, it is essential to analyze the long-term changes of surface albedo in Greenland at a longer time scale.
Surface albedo rules the actual energy income captured by the land surface, however, the changes of the land surface are quite complex. Although cloud and atmospheric climate forcing were reported to cause Greenland’s ice melt, a more interesting study indicated that atmospheric circulation of organic carbon particles, climate forcing by black carbon aerosols lead to the darkening of the ice sheet in Greenland and an earlier melting period of ice, which might reduce albedo of the ice surface; further, an increase in net radiation energy in turn also reinforces a massive melting of Greenland ice sheet [20,25–28]. In addition, snowfall with black carbon particles made the land surface show “dark snow” to some extent [29], which undoubtedly reduced the surface albedo [13,30,31]. A more interesting study suggested that dust from the Sahara could also affect the rate of ice melting in Greenland [32] by sampling ice cores. Obviously, the dark land background reduces albedo in the proximity of the land surface, which in turn promotes the melting of the local ice sheet and also increases the local surface runoff. At present, although the mechanism of action of microorganisms is still unclear, we think that this is also an important factor that cannot be ignored regarding the studies of albedo and melting ice. One possible explanation is that the physiological metabolic effects of microbes within the ice are activated as global temperatures increase, which leads to the melting of the ice and the decrease of albedo [30,33].

Several months ago, the Amazon fire triggered panic globally and regionally, and the research concerned indicated that the fire from tropical rain forests could also affect the polar ice and snow [6,34]. In recent years, the evidence documented by many studies showed that the smoke from forest fires had been transported to Greenland, with more than 3.3 million hectares of boreal forest in northwest Canada [35,36]. Overall, changes in surface cover directly or indirectly affect local albedo at a regional scale. Therefore, the highly multifactorial complexity and land surface processes that triggered albedo change in Greenland make it more necessary to conduct a long-term understanding regarding albedo changes.

Although we have found the rapid melting of the Greenland ice sheet, little is known about changes in albedo over extended periods of time. Additionally, the driving force behind the change in albedo remains unknown. Albedo changes could affect regional climate change to some extent, for example, through multiple climate feedback mechanisms [8,15]. Enough attention, however, is still not paid to the understanding between climate change and albedo to regard it as a fundamental climatic parameter in common research. In general, there are two main factors regarding global climate change: internal variability and external forcing (IPCC, Report, 2018). Aiming at the trend of surface albedo, in order to further analyze the contributors, we conduct the prevailing D&A (detections and attributions) analysis, and thus one of the main purposes of this study is to detect the signal of human activities. Obviously, the rising temperature is the root cause of Greenland’s ice melt [20,37], but there are still many unknowns for the mechanism of change in regional albedo in Greenland. In this study, the land surface albedo spatial-temporal changes were estimated based on satellite-derived GLASS products, in Greenland for a 37-year period (1981–2017). Further, based on observed and ensembles of CMIP5 simulations data, a preliminary detections and attributions analysis of albedo variations in Greenland was conducted adopting consistency testing of observed versus simulated data. To this end, the paper is structured as follows: Section 2 provides descriptions of the study area, the data set, and methodology. Section 3 presents the results obtained in this work. Section 4 includes a brief discussion regarding this study, and the following Section 5 summarizes some main conclusions.

2. Materials and Methods

2.1. Study Area

Greenland, the largest island in the world, is 2, 166, 313.54 km², which is located between the Arctic Ocean and the Atlantic Ocean. At high latitudes, the northern corner of Mauritius is located at 83°39′ N, while the southernmost corner of Farwell is located at 59°46′ N, with a north-south length of 2670 km, which is equivalent to the distance from the northern end of the Europe continent to the middle of Europe. The northeastern corner is located at 11°39′W, while the
western Alexandria is located at 73°08′W. The overall island belongs to the cold zone climate and the minimum temperature is around -70°C. The mean temperature, in the middle region, is -47°C. A number of studies in recent years confirmed that Greenland had encountered ice sheet melting over a large area (Figure 1). Therefore, Greenland’s melting ice may have changed the local climate and also is an important witness of global climate change [11].

![Sample plots of Greenland ice melt scene](image)

**Figure 1.** Greenland ice melt scene. Based on the Google Maps Tools ("Google-Collect" interface, a tool for scientific research developed on Google platform), we collected the underlying surface conditions of Greenland’s north (N), east (E), south (S) and west (W) regions.

2.2. Data and Materials

2.2.1. Observed Datasets

GLASS surface albedo product integrates several primary products produced by different data sources and inversion algorithms, which is a global albedo synthesis product with high precision and spatiotemporal consistency. The spatial range of GLASS surface albedo products are extended to the global land surface, with a temporal resolution of eight days, and the spatial resolution mainly includes two types: 0.05° and 1 km. In this study, the time range is from 1981 to 2017, and the spatial resolution is resampled as 0.05° regarding data we used. The GLASS data product link: http://www.geodata.cn/thematicView/GLASS.html, http://glcf.umd.edu/data. Generally, compared with the existing albedo products based on satellite data such as MODIS (Moderate-resolution imaging spectroradiometer), the GLASS data products we used have two advantages: 1) the long time period; 2) the higher spatial resolution. In detail, GLASS is a new set of global satellite data products jointly developed by the University of Maryland and Beijing Normal University, which is also one of the longest time periods albedo data products in the time series so far. It should be explained that, under the long period and wide view, a set of satellite data products with higher accuracy is necessary for our study. Compared with ground flux site observation data, the GLASS data product we used has higher accuracy and minor observation error [5,12,38], which can meet the requirements of this study.

2.2.2. Simulated Datasets

Coupled Model Inter-comparison Project 5 (CMIP5) as a standard experimental protocol for studying the output of coupled general circulation models expands our understanding of climate change regionally and globally, which allows the simulated climate to adjust to changes in climate
forcing regarding the different periods based on the targeted earth ecosystem in the future. Here, CMIP5 climate simulation outputs for the earth system were used in our study (data is open-access from the following service interface/port link: https://esgf-node.llnl.gov/projects/cmip5/). In our study, for further analysis of albedo variation in Greenland, outgoing and incoming shortwave radiation data were preferentially adopted (Table 1), considering that shortwave radiation is a major factor that affects the surface energy balance. The outputs from CMIP5 provide consistent simulations and support land and ocean applications. Because the simulated data sets we used are obtained from the multi-controlled experiments, thus we can obtain the cause of the observed variations with the help of mathematical statistics and hypothesis testing based on the combinations of simulated and observed data.

### Table 1. Data types and data sets of climate models used in the study.

| Name            | Affiliation/Country | Resolution |
|-----------------|---------------------|------------|
| bcc-csm1-1      | CN                  | 64×128     |
| bcc-csm1-m      | CN                  | 160×320    |
| BNU-ESM         | CN                  | 64×128     |
| GFDL-ESM2G      | USA                 | 90×144     |
| GFDL-ESM2M      | USA                 | 90×144     |
| GISS-E2-H       | USA                 | 90×144     |
| GISS-E2-H-CC    | USA                 | 90×144     |
| ipsl-cm5a-lr    | FRA                 | 96×96      |

#### 2.3. Methods

M-K trend test (Mann-Kendall), which is widely used in climate change studies [21], is introduced in our study to detect the albedo trend [39]. M-K trend test, typically, is a non-parametric method, which has strong robustness and stability in checking the significance of trends regarding the missing value and error value within space-time sequence, and which is expressed as the following:

\[
S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i)
\]  

(1)

Where \( n \) represents the total number of years. \( Xi \) and \( Xj \) are the data values in time series \( i \) and \( j \) (\( j > i \)), respectively; and \( \text{sgn}(x_j - x_i) \) is a sign function:

\[
\text{sgn}(x_j - x_i) = \begin{cases} 
  +1, & x_j > x_i \\
  -1, & x_j < x_i \\
  0, & x_j = x_i
\end{cases}
\]  

(2)

Then, we compute the variance \( \text{Var}(S) \):

\[
\text{Var}(S) = \frac{m(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18}
\]  

(3)

Where \( m \) is the number of tied groups (a set of data having the same value) and \( t_i \) is the number of data of tied group \( i \). In cases where the sample size \( n \) >10, the standard normal test statistic \( Z_S \) is computed as:
$Z_s = \begin{cases} 
\frac{S - 1}{\sqrt{\text{Var}(S)}}, & S > 0 \\
0, & S = 0 \\
\frac{S + 1}{\sqrt{\text{Var}(S)}}, & S < 0 
\end{cases}$

(4)

$Z_s$ is the indicator for the albedo trend. The testing of the trend is done at the specific $\alpha$ significance level. $|Z_s| > Z_{1 - \frac{\alpha}{2}}$ means there exists a significant trend in the time series, and positive $Z_s$ indicates an increasing trend and negative $Z_s$ indicates a decreasing trend. Here, in our study, $\alpha$ was set as 0.05. It is noted that the M-K trend inversion algorithm is based on pixels; therefore, longitude and latitude have been taken into account. In this study, according to the practical requirements, we focused on the following key issues before obtaining the albedo trend: 1), the annual albedo data obtained over time were independently distributed. In other words, the assumption of independence implied that the data were not continuously correlated over time. 2), our sampling unit was the monthly average albedo, further, the annual albedo was obtained by an average of 12 months ($n=37$, which meant that our samples were representative). 3), the collection and processing of sample data could ensure that those representative observations were unbiased and independent in the overall samples. Further, the independence assumption required that the time between samples was long enough, which made no correlation between measurements collected at different times.

3. Results

3.1. Seasonal Spatial Distribution in Albedo

Albedo could directly affect the net surface energy budget [8,15]. Seasonal albedo changes provide more help to our understanding of Greenland’s multi-year climate responses. Here, to gain an in-depth understanding of surface albedo change in the past 37 years in Greenland, we first obtained the spatial distribution of mean seasonal albedo retrieved from the GLASS albedo data products (Figure 2).

**Figure 2.** Mean seasonal albedo based on the GLASS satellite records from 1981 to 2017. (a) mean albedo in spring (March, April, May); (b) mean albedo in summer (June, July, August); (c) mean albedo in autumn (September, October, November); (d) mean albedo in winter (December, January, February).

The mean seasonal albedo was unevenly distributed across different seasons (Figure 2). From Figure 2, we can see that most of the albedo in the study area presented a high level during the past
37 years in Greenland, and the low albedo was mainly concentrated in the coastal zone of Greenland. Generally, middle Greenland maintained a high albedo which was mainly dominated by ice/snow layers. In coastal areas, the albedo was low relative to the high albedo in the mid-part of the study area due to massive ice melting, surface runoff, and plants triggered by the rising temperatures [40]. Further, for each mean seasonal albedo, we found that the mean albedo showed different spatial distribution characteristics, that is, it showed strong spatial heterogeneity. To some extent, the variation of spatial heterogeneity may also mirror the complex variation information of the underlying surface process in the past 37 years. Further, we found an interesting phenomenon: the mean albedo in the south of the study area was much higher than that in the north of the study area in spring but much lower than that in summer. Additionally, we found that the area demonstrated a high variation frequency across four seasons was located in the south of the study area, and a “boundary line” was easy to be recognized. One possible explanation was that this may be related to local variations in the atmosphere’s circulation as well as the local surface elevation [23]. In detail, variations in atmospheric circulation could cause slight changes in meteorological conditions locally; in addition, surface topography (elevation) and global ocean circulation may also contribute to albedo variation. However, this obvious region-shift effect regarding mean albedo in different seasons remained to be further investigated.

### 3.2. Seasonal Trend in Albedo

Albedo also differed significantly in its response patterns to different seasons. In Section 3.1, considering the polar night phenomenon in winter, we treated spring and summer as two important seasons, because the mean seasonal albedo showed some spatial differences in two seasons (i.e., “shift” effects between different seasons). To further mine the seasonal variation characteristics of albedo, we obtained the seasonal variation trend of albedo (Figure 3) based on the M-K method (Chapter 2.2).

![Figure 3](image_url)

**Figure 3.** Trends in seasonal albedo based on the GLASS dataset from 1981 to 2017. (a) spring albedo trend; (b) summer albedo trend; (c) autumn albedo trend; (d) winter albedo trend. (Grey areas indicate no significant trend; green areas indicate increasing trends, and magenta areas indicate decreasing trends; CI: 90%).

The trend analysis of long time series gives us a deeper understanding of surface albedo changes in Greenland during the past 37 years. Here, we paid more attention to the trend of albedo in summer and autumn. Our findings highlighted that the albedo trend differed in its response to seasonal variation as well as local climate change. As can be seen from Figure 3, most of the middle region showed an increasing trend in albedo among the different seasons. It is noted that the significantly increasing trend in the south of the study area is still detected among most seasons except summer. Our study found that the regions exhibiting a significant increasing trend were
mainly distributed in the middle region, but the coastal regions showed a significant decreasing trend. Further, a possible reason was that due to global warming, it has been found that there are a large number of low and medium level vegetation in the coastal areas of Greenland [1,14,41]. The northward movement of vegetation trace line in the Northern Hemisphere is very likely to exacerbate this trend of regional warming (because the vegetation still shows low albedo). Additionally, a possible explanation regarding the middle part of the study area showed a significant increasing trend that either cloud cover or a high-frequency snowfall occurred in the middle part of the study area, although these explanations still lacked detailed observed-based evidence. In conclusion, we can see from Figures 2-3 that the seasonal variation trend of albedo showed stronger spatial and temporal heterogeneity relative to the mean seasonal distribution throughout the 37 years.

3.3. Interannual Trend in Albedo

The variation of the inter-annual trend can mirror the internal variability of climatic variables despite the changes in regional climate that have been detected. Through the M-K algorithm, we obtained the inter-annual trends of surface albedo from 1981 to 2017 (Figure 4).

![Figure 4. Inter-annual variation of albedo based on the GLASS dataset from 1981 to 2017. The pink part indicates that the albedo showed a decreasing trend; the green part indicates that the albedo showed an increasing trend, and; the gray part indicates that no significant trend was detected. The right part denotes the inter-annual mean albedo profile along a latitude direction.](image)

As can be seen in Figures 4–6, the areas exhibiting a significant increasing trend in albedo were mainly distributed in the middle of the study area. In addition, there was a significant decreasing trend in the east and west of the study area. Further, our results were consistent with previous studies [19], and numerous studies had documented substantial melting of the Greenland ice sheet and increased surface runoff [7,13,42]. Our study showed that there was a general decreasing trend in albedo across Greenland. This decreasing trend in inter-annual variability was likely to enforce a direct local warming effect, although most of the decreasing trend was along the coastal region. In addition, there was no significant trend between the middle and coastal areas. Further, based on regionally spatial statistical analysis, we obtained a distribution plot of mean albedo along the latitudinal (N60°-N85°) profile (Figure 4, right part). From Figures 4–5, we can also see that the regions presenting significantly statistical characteristics were mainly concentrated in N65°-N70°.
Figure 5. Statistical distribution of inter-annual variation of albedo based on the GLASS dataset in different regions from 1981 to 2017. Three groups random samplings (grid-based) at each location were performed, and finally, the average of the three samplings was used as the result for that location. The abscissa represents the albedo value; the ordinate represents the different sampling areas, where, ’1–2’ denotes middle Greenland, ’3’ denotes northern, ’4’ denotes western, ’5’ denotes southern, and ’6’ denotes eastern.

Figure 6. Time series of inter-annual variation of albedo (ABD) based on the GLASS dataset in different regions. M1 and M2 denote middle Greenland, N denotes north, W denotes west, S denotes south and E denotes east.

We found that weak decreasing trends were detected in autumn (Figures 3–4), and conversely, the middle region still showed an increasing trend over larger areas, implying that there may be a typical local cooling effect in autumn, which, given the lag of the climatic effect, was likely to result in an increasing trend in albedo over large areas in the middle part of study area in winter. Thus,
the climate feedback mechanism of ice-albedo was expected to be enhanced. According to our analysis, the coastal region was likely to tend to warm (showing a decreasing trend in albedo), while the middle region was likely to tend to cool (showing an increasing trend in albedo), and these two opposing trends would affect the regional climate around the boundaries of these two trends, i.e., it was likely to alter the snowfall and surface moisture in the boundary region [2,3,15]. Based on this hypothetical trend, we argued that albedo would show a decreasing trend in overall areas gradually in the future. Of course, further studies are necessary in the future.

3.4. Coupled near Surface Temperature and Albedo

The change of albedo would impact the net radiation energy of the surface [15]. Considering the underlying surface of Greenland is relatively simple, as well as the albedo can mirror the redistribution process of solar energy received by the land surface, here, in order to conduct comparison and verification regarding the inter-annual variation of albedo, we made an analysis on the near-surface temperature (2 m) of the study area. This parameter is the temperature of air at 2 m above the surface of land, which is calculated by interpolating between the lowest model level and the Earth’s surface (in detail, the data covers the Earth on a 30km grid and resolves the atmosphere using 137 levels from the land surface up to a height of 80km). The ERA5 monthly averaged data on single levels (reanalysis: 0.25°×0.25°) from 1981 to present was introduced in this study (the data descriptions refer to https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis). To this end, we obtained the linear trend of the temperature in the study area and the standard deviation of the trend slope (Figures 7–8), where the former can capture the linear trend of the air temperature and the latter can obtain the degree of statistical difference regarding the temperature trend in the study area. In order to analyze the temperature variation trend of the study area in the last 37 years in detail, we analyzed it in two steps: first, we obtained the temperature trend from 2008 to 2017 (Figure 7, last 10 years); second, we also obtained the temperature trend from 1981 to 2017 (Figure 8, last 37 years).

**Figure 7.** Trend of near-surface air temperature (a), and trend slope standard deviation (b) from 2008 to 2017 (last 10 years) based on the ERA5 monthly averaged data on single levels.
Figure 8. Trend of near-surface air temperature (a), and trend slope standard deviation (b) from 1981 to 2017 (last 37 years) based on the ERA5 monthly averaged data on single levels.

Our study showed that in the last decade (Figure 7), the northwest and eastern parts of the study area experienced much more warming while the southern part of the study area showed a significant cooling trend. The greatest uncertainty of temperature trends was mainly concentrated in the north of the study area. Although numerous studies have revealed that the northeast, northwest, and southwest of the study area had encountered significant melting processes [7,43], our study shows that increasing temperature is more significant in the west and southeast of the study area with middle confidence. However, based on the analysis of the results in the last decade, we found that the eastern (southeastern) part of the study area belonged to a stable zone of increasing temperature (Figure 7). Although the southwest of the study area showed a warming trend in the last 37 years (Figure 9), it had shown a cooling trend in the last decade. In addition, in Sections 3.2 and Sections 3.3 we reported that the albedo in the middle Greenland region showed different spatial-temporal characteristics (that is, a strong heterogeneous) in terms of inter-annual variation and seasonal trends, and we could also see from Figure 9 that the historical observations were almost consistent with the results of the climate model simulations. For southern regions with large temperature ranges, the results of both the historical simulations (control) and the current emissions scenarios (RCP8.5) showed that disturbances and changes in local climate had been detected in southern and middle Greenland (Figure 8), which was consistent with our observed variations in albedo. Therefore, this also demonstrated on the other hand that variations in albedo could mirror the feasibility and preliminary scientificity of regional climate change in practice, although the feasibility still needs to be investigated and validated further.
3.5. A prevailing Analysis in Detection and Attribution

Detections and attributions of climate change, as a way of understanding causation of climate change, which typically seek to assess whether observed changes are consistent with the expected response, has received much attention over the last 20 years [44]. Detection of change is defined as the process of demonstrating that climate had changed in a defined statistical sense, without providing a reason for that change, while the attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence (IPCC, 2007, 2019; AR4 and AR5) [44]. The definition of detections and attributions has benefited from many scholars’ efforts from the original to the present, which has become an important theoretical basis and tool for us to study the causality of climate change regionally and globally.

It is undeniable that the methods of detections and attributions are effective in the study of global climate change and the results obtained are always playing an important role in recognizing the evidence of human activities regarding current climate change [44, 45]. However, there is still a great deal of uncertainty, such as simulated data and models, in D&A at the regional scale. Nevertheless, to minimize the uncertainty in regional climate analysis, we adopted the average-based strategy because this one could reduce the uncertainty to some extent [46]. In addition, the consistent test of different climate ensembles was also the key to D&A. Through the statistical analysis in terms of both observed and simulated data, here, the downscaling of climate simulation data was also introduced in this study [47].

Drivers analysis of regional surface albedo changes is critical to understanding the local albedo changes to different climate responses. To obtain the reasons for the variation of regional albedo,
we firstly used the climate simulation dataset provided from CMIP5 based on 20 climate patterns and employed the multi-model assembles to analyze the variation characteristics of Greenland’s surface radiation. The experimental design included the control and treatment groups for the study. Factors involved in our experiments were shown as following: historical data sets (both natural and human activities); carbon dioxide data sets (typical greenhouse gases, only); historical data sets (natural factors, only); historical data sets (sulfur concentration only, refer to aerosols) (Figure 10).

Our experiments were divided into the above four groups and each group used a comparative analysis strategy to obtain the correlation between different factors combinations and observed values, that is, the correlation detection of the response.

![Figure 10](image_url)

**Figure 10.** Surface shortwave outgoing radiation (rsus) and shortwave incoming radiation (rsds) for long-term climate simulation datasets (CMIP5). Among them, (a) presents the total historical simulation data (including both natural and human-induced factors) from 1979 to 2008; (b) presents the total historical simulation data (greenhouse gas emissions scenario, four times carbon dioxide) from 1979 to 2008; (c) presents the historical simulation data (including natural factors only) from 1850 to 2012; (d) presents the simulated data from 2001 to 2030 (considering aerosols only, taking the sulfur concentration in the atmosphere as a controlled parameter).

After averaging overall the climate simulation datasets, we obtained the surface outgoing and incoming radiation distribution for Greenland as shown in Figures 10–11. Since the land surface energy balance is mainly determined by the shortwave band in practice, it is necessary to obtain accurately the net radiation budget of the surface under different controlled conditions for understanding the change of albedo. Here, we focused on shortwave outgoing radiation and shortwave incoming radiation. From Figure 10, we can see that, except for the natural factors, generally, the shortwave incoming radiation was higher than the shortwave outgoing radiation under different controlled conditions. The averaged value of incoming and outgoing radiation was 200 W/m² and 159 W/m², respectively. The simulated results of the treatment group for natural factors showed that the incoming radiation was mainly closed to other ones (Figure 10c), but the outgoing radiation was significantly higher than other treatment groups (80±3.5 W/m², higher than...
average in most groups), which indicated that the direct result of natural factors might cause higher outgoing radiation in a higher latitude zone, despite that this argument might not be expected to be a correct explanation across the global zone, except in a high latitude.

From Figure 11, we can see that the results of both the total historical simulations and the greenhouse gas simulations showed that the middle and northern parts of Greenland presented high outgoing radiation. In contrast, the southern parts were mainly dominated by low-level incoming radiation, which showed a significantly differential distribution in most of Greenland. When natural factors only were taken into account, the corresponding experiment results showed that the outgoing and incoming radiation showed obvious uniformity distribution characteristics, and there was no obvious clustering effect at a spatial scale (Figure 11c). However, we found that even if this spatial clustering effect was not obvious enough, the northern part, generally, showed higher outgoing and incoming radiation. Further, the sulfur concentration in the aerosol significantly impacted the surface outgoing radiation, particularly in the middle and northern parts. Therefore, this result suggested that the albedo in the middle and northern Greenland could be altered significantly if the sulfur concentration in the aerosol maintained the current emissions scenario in future periods. In other words, the checking of the response of regional albedo to the changing climate, indeed, is very complex.
**Figure 11.** The spatial (refer to latitude) and temporal (refer to annual) variations of the surface shortwave outgoing radiation (rsus) and shortwave incoming radiation (rsds) for the long-term climate simulation datasets (CMIP5) in Greenland. (a) denotes the total historical simulation data (including both natural and human factors) from 1979 to 2008; (b) denotes the total historical simulation data (greenhouse gas emissions scenario, four times carbon dioxide) from 1979 to 2008; (c) denotes the historical simulation data (including natural factors only) from 1850 to 2012; (d) denotes the simulated data from 2001 to 2030 (considering aerosols only, taking the sulfur concentration in the atmosphere as a controlled parameter).

The spatial distribution of the outgoing and incoming radiation of the shortwave shows different distribution characteristics under various control conditions (Figure 11). The simulated results of CO2 greenhouse gas emissions (4*CO2: emissions scenario) were more consistent with the results of historical total simulation (both natural and human activities), so the increase of CO2 emissions only could not significantly affect the shortwave outgoing and incoming radiation. Further, comparing the historical simulation data (natural factors only) with the total historical simulated results, we found that natural factors more significantly impacted on the shortwave outgoing and incoming radiation over the entire study area; and accordingly, both outgoing and incoming radiation was higher than those of the historical total simulated results (outgoing radiation: +6.7%, incoming radiation: +5.2%). Furthermore, the outgoing radiation in the middle and northern regions increased by 24.1% and 10.3%, respectively compared with the historical total simulation when the aerosol factor of containing sulfur was only considered. We also found that the incoming radiation stimulated by the sulfur-containing aerosols had been significantly enhanced in the middle (increase, +16.5%) parts of the study area compared to the historical total simulation.

To minimize human subjective effects (possible uncertainties arising from the experimental design itself as well as human subjective factors on D&A in regional climate, further reading please refer to Ref.44), we designed 10 experimental combinations based on four sets of simulated data (which, naturally, were grouped into four forcing categories, referring to the descriptions in Chapter 2.2.2). Prior to this, we also did some correlation analysis, however, we found it difficult to capture the signal of key factors (e.g., human-induced) by correlation analysis alone. Obviously, no useful information could be obtained by using simple correlation analysis only, therefore, we abandoned this simple method and its corresponding figures without any significance and it was not presented in our study. This has to make us turn to other methods in order to make a plausible explanation for our proposed scientific hypothesis. Further, by employing non-parametric tests, we performed a consistency analysis for all combinations (simulated data and observed data). It is noted that not all test combinations would be able to be detected, in other words, although our test combinations reduce some human subjective factors, there is still some uncertainties. Finally, only five of the ten combinations were detected and few contributors were recognized based on the assessed probabilities.

As described above, the responses of multiple climate forcing to regional climate are complex. As can be seen from Figure 10, by comparing the simulated and observed values, we found that greenhouse gasses forcing (carbon emissions) and aerosol forcing were the significant contributors (probability coefficient: 0.46; p<0.05)( Figure 12e). Further, we found that it was difficult to detect
effective factors simply by a single factor. Through the combinations of multiple factors, the observed value and the control group were analyzed, and the results obtained had a good explanatory ability. In our study, we also found that once we incorporated the natural forcing into our analysis system, it was not difficult to find that the probability was significantly lower (decrease by -0.16; p<0.05) (Figure 12e–f), so we tentatively argued that the natural forcing was not the main reason for albedo changes in Greenland. According to our results, the combinations of multi-pattern responses are the key to detecting the change factor, although the current state-of-the-art methods are still difficult to minimize the uncertainty of the assessment. Among them, people, in the process of developing climate models, often based on some prior knowledge, that is, assuming that the observed values conform to a certain response pattern, which no doubt indirectly increases the uncertainty of the results [44]. It is necessary to address that our results remain somewhat uncertain. In short, the change in regional climate is mostly influenced by multiple factors. In other words, relying on only a few single factor analyses, it is difficult to capture meaningful information in D&A research.

![Figure 12. The prevailing analysis in detection and attribution in different groups. The observed value represents the actual observed albedo trend from GLASS dataset product; the simulated results(CMIP5): (a) Aerosol forcing only; (b) Greenhouse forcing and aerosol forcing only; (c) Greenhouse forcing, aerosol forcing, and natural forcing; (d) Aerosol forcing and natural forcing only; (e) Greenhouse gas forcing and aerosol forcing combine with the historical total simulation; (f) Historical total simulation, Greenhouse forcing, aerosol forcing, natural forcing together.](image)

### 4. Discussion

As mentioned in the introduction part, the study of Greenland’s response to global climate has been a hot topic and within IPCC’s reports, which focuses on two aspects: the observation of ice sheet and the D&A analysis of the climate globally and regionally (IPCC, 2019)[1,3,44]. In this study, we selected Greenland as the study area, based on the typical climate feedback mechanism of albedo-ice, and focused on analyzing the spatiotemporal variation of surface albedo in Greenland in the last 37 years. In addition, a prevailing D&A analysis was adopted to recognize the signal induced by human activities regarding albedo variations. However, our study still has much to discuss further.

1. **Uncertainty of satellite observed data**

   The land surface albedo is defined as the hemispheric reflectivity of a surface integrated over the entire solar spectrum. The surface albedo is not only needed to estimate the surface energy balance, it is also an indicator of many physical aspects of the surface, such as ice/snow thickness and runoffs. High spatiotemporal precision in surface albedo data is necessary for the understanding of climate change globally and regionally [38]. The GLASS albedo data used in this
study is a collection of two-stage data products. In the first stage, the GLASS data product is overestimated or underestimated in the ice/snow cover region because the product’s algorithm is mainly based on the statistical empirical model of multi-source remote sensing data; in order to reduce the uncertainty of ice/snow in the albedo inversion, the GLASS albedo product is corrected based on a new ice/snow inversion model in the second stage. Thus, there may be some errors in capturing albedo trends over the past 37 years in Greenland due to the high sensitivity of albedo in ice-snow cover areas. Although the GLASS data products have considered the effects of clouds, there are still some uncertainties in the quality control data, especially in high latitude areas, which could also increase indirectly the error of the observed data. In addition, since Greenland would experience polar night phenomena during the winter period, this means that surface radiation is mainly dominated by outgoing radiation because the incoming radiation is quite limited, which would also introduce errors to our analysis. In our study, we paid more attention to summer albedo changes; however, for studies that deeply mine Greenland surface processes with climate change, we believe that the possible time-delay effects between spring and autumn due to surface process changes and climate change should also be appropriately considered in future studies. One of the important causes triggering global climate change (e.g., temperature) is the disturbance of the Earth’s energy balance, and albedo is a key factor in determining energy balance. Considering that the radiation energy obtained by the sensor is largely determined by the complex underlying surface, we also emphasize that for the energy balance of the surface, without making any distinction, the definition of albedo is approximately equivalent to the definition of surface albedo [48]. In addition, human activities have led to increases in well-mixed greenhouse gases, as well as changes in an atmospheric concentration such as sulfate aerosols, and it is clear that human activities have caused significant impacts on the global climate [49,50]. Multi-source observed satellite records are expected to contribute to the multidimensional perception and understanding of global climate change.

2. Uncertainty of global climate simulations outputs

The global climate patterns outputs released by CMIP5, which are mostly based on statistics and physics assumptions, were used in our study. This means that in all the outputs we used there may exist uncertainty. Complex surface processes are difficult to be parameterized accurately in climatic model sets; in addition, when regional simulation results are combined with global model ones, errors are inevitable in the processing of model data, such as downscaling processing of climatic models. Further, most of the simulated radiation in the current climate model sets are based on atmospheric physical processes, such as simulations of incoming and outgoing radiation; this means that simulations of surface radiation budget rely heavily on radiation budget simulations at the top of the atmosphere, and thus atmospheric conditions could bring some uncertainties to the land surface radiation simulations, such as clouds and aerosols. The monthly mean near-surface air temperature in ERA5 was also introduced in this study, and to capture the trend of near-surface air temperature in Greenland, we used the default linear trend algorithm in the data platform rather than the MK algorithm, and it should be mentioned that the results of the trends obtained by these two algorithms could not significantly affect our trends analysis although there may be some errors. Additionally, it should be highlighted that trying to capture a trend from temperature anomalies might be a better choice when analyzing the coupled near-surface air temperature. In short, current climate model outputs could estimate surface processes in most cases, however, the development of novel radiation simulation datasets that consider complex land surface and atmospheric processes is urgent in the future.

3. Trend retrieval and albedo-ice sheet feedback mechanism

Based on the analysis of the GLASS albedo data, we found that surface albedo in Greenland generally showed a decreasing trend over the past 37 years, which was consistent with existing studies [51]. This trend may trigger a local warming effect. In addition, in our study, we also found that the albedo in central Greenland showed a significant increasing trend. It should be emphasized that the decrease of surface albedo increases the net radiation energy of the surface, however, the increase of net radiation energy could not only cause the rising of surface temperature but also may
increase the evapotranspiration of the local surface, which may, in turn, cause the change of local snowfall under atmospheric circulation. The atmospheric circulation anomaly in central Greenland has not been studied specifically so far, and we indicate that the increasing trend of albedo in central Greenland may be induced by abnormal snowfall in ice surface or latest bare-ice, but this needs further studies to support and check that possibility. In addition, the studies regarding the offset mechanism between the increasing albedo caused by abnormal weather events (e.g., extremely cold days and snowfall) and the decrease of albedo caused by the darkening surface may provide meaningful help to unveil the albedo–ice feedback climate mechanism. In short, the climate model ensemble provides an important reference for us to recognize climate change; the multi-source remote sensing observation data recorded by satellites provide the prior knowledge for the development of global climate models. The new coupled climate model ensembles are expected to deepen the understanding of future climate change, especially for polar climate change. Additionally, more advanced algorithms regarding global climate patterns are expected to be developed in the future. Although global warming may be a fact, we need to emphasize that the role of albedo in climate change remains to be further investigated.

4. D&A in regional climate

Unlike at the global scale, D&A always has been a complex problem [44,46,52] at the regional scale. As most researchers begin to use climate models for regional applications, a common approach is to average all climate models, which is considered as a better choice at the global and regional scale although the detected results in regional climates are often attached to large uncertainties [46]. Unknown feedbacks within the climate system are considered as one of the uncertainty factors. However, it is difficult to properly mine and evaluate these feedbacks which may alter the expected response patterns (e.g., climate feedbacks related to ice/snow surface, surface runoff). Although the climate effects at high latitudes are often overestimated in the available climate data, this is inevitable and, to be precise, is likely to be determined by both the D&A itself and a climate dataset. In detail, on the one hand, the D&A we used in this study was conducted based on statistical principles, however, quantitative assessments of uncertainty were still lacking. On the other hand, the subjectivity of the researchers when choosing the climate model outputs could also have a certain impact on the attributions analysis. It should be pointed out that, in our study, greenhouse gas emissions induced by human activities may be overestimated in the attribution analysis because we used a 4×CO2 emission scenario. To date, some scholars have pointed out that if there were more than one causal factor to be considered, regression models cannot be used because several key regression coefficients could not be mapped correctly based on a single scalar observation only [44,46]. Observed noise and short time observed sequence, as well as limited precision, make it difficult to obtain high precision internal climate variability by the D&A analysis only. Although we could also choose climate models based on the regional difference and weight, this method is difficult to implement in practice. Finally, we adopted the averaged results of multiple models to conduct D&A analysis.

5. Conclusions

Climate change in the polar region has always been a hot issue within global change. Greenland, as the largest ice-covered island, has been indirectly affected by anthropogenic activities. Albedo, as a key climatic parameter, is strongly associated with local temperature changes in Greenland. In this study, we used the GLASS albedo data product to obtain the trend of land albedo in the past 37 years in Greenland based on the M-K non-parametric test method. Our study found that albedo showed a generally decreasing trend (-0.013 ± 0.001 decade⁻¹, p<0.01) at the interannual scale and a strong heterogeneous distribution at the seasonal scale. Further, we introduced the global climate patterns outputs in our study. Through the verification and consistency analysis regarding both the observed results and the simulated results, we conducted D&A analysis based on natural and anthropogenic factors. Finally, we found that both the Greenhouse gas forcing and aerosol forcing (46.1%) induced by anthropogenic activities in the past 37 decades were likely to be the main drivers for land albedo changes in Greenland. In short, the
changes in greenhouse gases and aerosols as a result of human activities have led to changes in the albedo of the Greenland ice sheet. Although the surface albedo feedback is generally less variable than cloud feedback, it is strongly associated with local temperature changes in Greenland. Therefore, this study based on a coupled dataset provides a potential pathway to understanding climate change on a regional scale. Finally, our research is expected to provide more insights into Greenland’s climate change. A comprehensive understanding of long-term changes in albedo will deepen our understanding of a typical self-reinforcing mechanism (e.g., albedo–ice) in the local climate feedback, which is important for conducting climate governance strategies, and monitoring or mitigating climate change in the future.

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