Greenland Monthly Temperature Reconstruction Over The Last 10,000 Years

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Greenland monthly temperature reconstruction over the last 10,000 years

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Highlight

1. Monthly temperature data over past 10,000 years was reconstructed in Greenland.
2. The temperature of September to May showed a significant increasing trend at the 0.05 level during period 9700 B. C. E. ~ 2019 C.E., and the increasing rate is 0.0017 ~ 0.0058 ℃ every two decades. However, the temperature of June to August showed a significant decreasing trend, and the decreasing rate is -0.0035 ~ -0.0040 ℃ every two decades.
3. This study provides guidelines for the study of climate change and Greenland ice sheet mass balance.

Abstract

Greenland is the biggest island in the world, and the area of snow and ice is the second largest in the world, which is only smaller than Antarctic ice sheet. Studying the temperature change of the island is important for ice sheet melting, especially the summer temperature. In this study, we reconstructed monthly temperature data over past 10,000 years using ice core data, meteorological observation data and European reanalysis data, and linear regression equation– residual correction method was used. And the results are as follows: The temperature of September to May showed a significant increasing trend at the 0.05 level during period 9700 B. C. E. ~ 2019 C.E., and the increasing rate is 0.0017 ~ 0.0058 ℃ every two decades. However, the temperature of June to August showed a significant decreasing trend, and the decreasing rate is -0.0035 ~ -0.0040 ℃ every two decades. The climate change can be divided into four increasing periods, namely, period 9700 B. C. E. ~ 9600 B.C.E, period 9400 B. C. E. ~ 7720 B.C.E, period 6240 B. C. E. ~ 6000 B.C.E, and 1800 C.E. ~ 2019 C.E., and three decreasing periods, namely, period 9600 B. C. E. ~ 9400 B.C.E, period 6340 B. C. E. ~ 6240 B.C.E. and 6000 B.C.E. ~ 1800 C.E., and one stable periods, namely, 7720 B.C.E. ~ 6340 B.C.E. And the differences of temperature change rate of different altitudes of the same period and month is not obvious. And the temperature change rate in Winter is larger than that in Summer. The dataset can provide data basis for the study of Greenland ice sheet mass balance.

Key words: Greenland· Ice core· Temperature reconstruction· Monthly· Climate change

1. Introduction

Polar glaciers are extremely sensitive to temperature change, the polar glaciers are retreating

in different degrees because of global warming. Some studies have shown that there is a polar amplification phenomenon of temperature change in the Arctic, that is, the temperature change in the Arctic is twice that of the global average temperature (Cohen et al., 2014). This amplification phenomenon aggravates the melting of polar glaciers, and the amount of sea ice around the Arctic is further reduced due to climate warming. Greenland is the largest island in the world, and has the second largest ice sheet in the world only after the Antarctic ice sheet. The study of the change characteristics of the ice sheet mass balance in this area can predict and evaluate its impact on the global sea level, which has certain guiding significance for the political, economic and cultural development of the world's coastal countries. Temperature and precipitation are the most basic and important variables in water balance modeling. Temperature not only affects precipitation patterns, but also plays a decisive role in the onset and cessation of ablation. Therefore, the study of temperature change characteristics in Greenland can provide a basis for understanding climate change and further study of water balance change in this area. Most meteorological observation records can only date back to past 150 years, which limits our understanding of long-term climate change (Kobashi et al., 2010). Ice core data extends the temperature records to the past 10,000 years by temperature proxy data.

Scientists collected some ice cores samples in Greenland in the 1990s, and then many scientists reconstructed temperature dataset using these ice cores data. Kobashi et al. (2017) reconstructed Greenland Summit temperatures dataset over past 10,000 years using argon and nitrogen isotopes in GISP2 ice core, and they analyzed temperature change characteristic and driver factor influencing temperature change. The reconstructed temperature dataset can better describe temperature change characteristic, such as 9.2 ka event, 8.2 ka event and Holocene Thermal Maximum and so on. And volcanic eruptions are important driving factor to temperature cooling. Johnsen et al. (2001) reconstructed palaeotemperature record from Greenland six ice-core stations using conversion function method between $\delta^{18}O$ record and temperature, or modeling inversion of the bore temperature profile. The reconstructed results had similar characteristic using different methods. Steffensen et al. (2008) analyzed the last two abrupt warming events around Younger Dryas cooling event using NGRIP, GISP2, GRIP and DYE-3 ice core$\delta^{18}O$ record. Buizert et al. (2018) reconstructed seasonally temperature change over past 10,000 years by merging ice-core

reconstructions with transient climate-model simulations, and analyzed the spatial distribution characteristic of last deglaciation and Holocene temperature. Orbital forcing was the important influence factor for summer temperature, whereas greenhouse gas and AMOC forcings are important influence factors for winter temperatures. Unlike previous studies, Badgeley et al. (2020) used paleoclimate data assimilation method to reconstruct temporal and spatial temperature of Greenland Ice Sheet over the last 20,000 years.

Since most of the ice core data are annually data, the current temperature analysis is also focused on annually data, and most of the research is focused on temperature reconstruction of a single ice core site. However, glacier melting mainly occurs in summer, and most of the other seasons are the accumulation stage of glacier energy. Therefore, it is more important to reconstruct monthly temperature datasets in order to better study the characteristics of glacier mass change and glacier melting change. Therefore, this chapter focuses on the reconstruction of the monthly temperature dataset covering the whole island in the past ten thousand years and analyzes the characteristics of the monthly temperature changes in the past ten thousand years, so as to lay a foundation for the further study of the water balance and climate change in Greenland.

The specific structure of this chapter is as follows: 2. Study area and data; 3. Methods; 4. Results and discussion; 5. Conclusions.

2. Study area and data

2.1 Study area

Greenland is located at 59°46' N ~ 83°39' N, 11°39' W ~ 73°08' W, and the north-south length and the east-west width of the Island are 2 670 km and 1 050 km, respectively. Greenland is the largest Island in the word, the whole area is 2 166 086 km^2. 82% of the Island area is covered by ice and snow, and the area of ice and snow is 1.8×10^6 km^2, the ice volume is 3.0×10^6 km^3, the max ice thickness is 3 367m. Greenland is surrounded by oceans, and the north, east, west, southeast and southwest part of the Island is surrounded by Arctic Ocean, Greenland Sea, Baffin Bay, North Atlantic Ocean, and Davis Strait, respectively, which is easily affected by sea current. Arctic Ocean and North Atlantic Ocean affect the exchange of cold and warm current of the Island. The capital of Greenland is Nuuk, the total population is 555 877 in 2018. Greenland is Arctic climate, the change of climate is easily affected by ocean-atmosphere General Circulation index, such as Greenland

Block Index (GBI), North Atlantic Oscillation (NAO) and so on. The Island can be divided into seven regions. The climate in each region is different. And the temperature in south region is higher than that in north region, the maximum temperature is higher than 10℃ in south region, and the minimum temperature may be lower than -40 ℃ in the north region. And sometimes the temperature in ice sheet is lower than -70 ℃ in winter. The temperature in the island is easily affected by foehn wind, which can cause drastic changes in temperature.

2.2 Meteorological observation data

The monthly coastal meteorological observation data in Greenland was downloaded from Danish Meteorological Institute (DMI), and the website is: https://www.dmi.dk/publikationer/. There are 9 weather stations used in this study, namely, 4202 Pituffik, 4211 Mitt.Upernavik, 4221 Mitt.Ilulissat, 4250 Nuuk, 4270 Mitt.Narsarsuaq, 4272 Qaqortoq, 4320 Danmarkshavn, 4339 Ittoqqortoormiit and 4360 Tasiilaq. Because of the bad climate, acquiring the meteorological observation data in Greenland is very difficult, and there were some gaps in this data. To analyze change characteristic of the monthly air temperature, we fill the gaps using Jiang's Methods (Jiang et al., 2020). And the time span of coastal meteorological data is from 1961 to 2019.

The monthly inland meteorological observation data in Greenland was downloaded from this paper "Surface climatology of the Greenland ice sheet: Greenland Climate Network 1995-1999" (Steffen and Box, 2001). And there are five weather stations used in this study, namely,01 Swiss Camp,08 DYE-2,12 NASA-E,07 TUNU-N and 06 Summit. And the time span of this data is from 1995 ~ 2001. Fig. 1 shows the spatial distribution of the coastal and inland weathers stations.

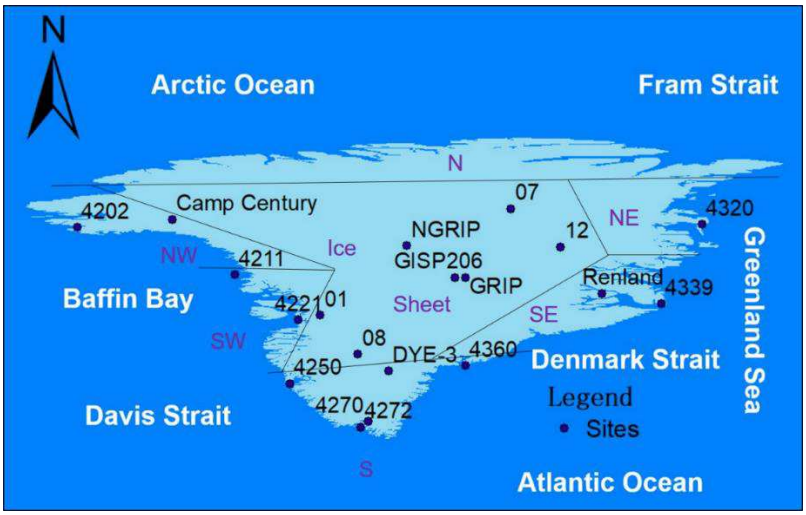

Fig. 1 Location of weather stations.

2.3 Ice core data

The ice cores data were downloaded from NOAA paleoclimatology data website, and the website is: https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets. We used $\delta^{18}O$ to reconstruct temperature change over the past ten thousand years. And there were six ice cores used in this study, namely, Camp century, NGRIP, GRIP, GISP2, Renland and DYE-3. The time resolution of the data is 20 years, and the time span of this data is from 9700 BC to 1960 AD. From Fig. 1, we can see that the distribution of these ice cores is uniform in the whole ice sheet, it means that the data is representative.

2.4 European Centre for Medium-Range Weather Forecasts data

We used ERA40 and ERA5 data in this study to extend inland temperature data and acquire temperature spatial distribution information of Greenland, respectively. And the data were downloaded from the following website: https://apps.ecmwf.int/datasets/data/era40-mnth/levtype=sfc/ and https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means?tab=overview, respectively. The time span of ERA40 dataset is from 1958 to 2001, and the data resolution is 0.75°×0.75°, but it was interpolated to 0.125×0.125° in this study. The resolution of ERA5 data is 0.1×0.1°, which spans from 1970 to 2020. Because these datasets cover global area, it's not accurate when used in a specific area. In this study, quantile-Mapping method was used to correct the deviation of temperature data.

157 Table 1 Station information. Lon represents Longitude, Lat represents Latitude, Ele represents Elevation.
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Station number	Station name	Lon（°）	Lat（°）	Ele (m)	Time span (Year)	Length(m)	Drilling Time (Year)	Sources
4202	Pituffik	76.53	-68.75	77	1961 ~ 2019	——	——	DMI
4320	Danmarkshavn	76.77	-18.67	11	1961 ~ 2019	——	——	DMI
4211	Mitt.Upernavik	72.78	-56.13	126	1961 ~ 2019	——	——	DMI
4221	Mitt.Ilulissat	69.23	-51.07	29	1861 ~ 2019	——	——	DMI
4339	Ittoqqortoormiit	70.48	-21.95	65/70	1961 ~ 2019	——	——	DMI
4250	Nuuk	64.17	-51.75	54/80	1961 ~ 2019	——	——	DMI
4270	Mitt.Narsarsuaq	61.17	-45.42	27	1961 ~ 2019	——	——	DMI
4272	Qaqortoq	60.72	-46.05	32	1961 ~ 2019	——	——	DMI
4360	Tasiilaq	65.6	-31.63	50	1961 ~ 2019	——	——	DMI
07	TUNU-N	78.02	-33.99	2113	1997 ~ 2017	——	——	GC-Net
12	NASA-E	75	-30	2631	1997 ~ 2017	——	——	GC-Net
01	Swiss Camp	69.57	-49.32	1149	1997 ~ 2017	——	——	GC-Net
06	Summit	72.58	-38.5	3254	1997 ~ 2017	——	——	GC-Net
08	DYE-2	66.48	-46.28	2165	1997 ~ 2017	——	——	GC-Net
——	Camp Century	77.17	-61.13	1885	9700B.C.E.~1960C.E.	1387	1966	Vinther,2009
——	NGRIP	75.1	-42.33	2917	9700B.C.E.~1960C.E.	3090	1996 ~ 2004	Vinther,2009
——	GRIP	72.58	-37.64	3230	9700B.C.E.~1960C.E.	3238	1993	Vinther,2009
——	GISP2	72.58	-38.48	3200	9700B.C.E.~1960C.E.	3208	1993	Stuiver,1995
——	Renland	71.3	-26.7	2350	9700B.C.E.~1960C.E.	325	1988	Vinther,2009
——	DYE-3	65.18	-43.83	2480	9700B.C.E.~1960C.E.	2037	1979 ~ 1981	Vinther,2009

3. Methods

In this study, the $\delta^{18}O$ value was converted into a specific temperature value by using the conversion function method. A quantile mapping method was used to correct the bias between monthly inland temperature observation data and ERA40 temperature data, and we employed Pearson correlation analysis to measure the linear correlations between annual temperature and monthly temperature at the same weather station, and the linear correlations of temperature between adjacent meteorological stations. We also used linear regression equation to calculate the relationship between annual temperature and monthly temperature, and residual correction method was used to convert annual temperature data to monthly temperature data. Based on the spatial distribution characteristics of ERA5 temperature data, the spatial distribution characteristics of monthly temperature in the past ten thousand years were reconstructed.

3.1 Conversion function method

$\delta^{18}O$ record is a good proxy for environmental temperature, but the relationship between $\delta^{18}O$ and temperature is complicated, because many factors affect the isotopic composition, and these factors are different in different climate (Cuffey and Clow, 1997). In this study, conversion functions collected from many references were used to convert the $\delta^{18}O$ record into a specific temperature value (cuffey et al., 1995; cuffey et al., 1997; Kapsner et al., 1995; Johnsen et al., 1995; Johnsen et al., 1989), and we adjusted these functions to make the bias of temperature between this paper and Buizert (2018) less than 3 ℃.

3.2 Quantile-Mapping method

ERA40 is a global-scale raster dataset, and there exists bias between this dataset and true temperature in local study area. In this study, we used Quantile-Mapping method to correct the bias. It builds conversion function between meteorological observation data and reanalysis data according to cumulative probability distribution function, and then we use the conversion function to correct the reanalysis data in a different period. It has been used in temperature and precipitation data correction, and the corrected results were better. And the commonly used quantile correction method can be divided into two kinds of correction based on parameter method and non-parameter method. If the meteorological observation data and reanalysis data satisfy hypothesis better, parameter

method can make a good result, or the results may be bad. And there is no hypothesis in non-parameter method.

In this study, we used two parameter methods (namely, linear and scale method) and five non-parameter methods (namely, QUANT-linear, QUANT-tricub, RQUANT-linear, RQUANT-tricub and SSPLIN method) to build the conversion function between inland meteorological observation data and ERA40 data during period 1995 ~ 1999, and the inland meteorological observation data was used to verify the accuracy of the selected methods during period 2000 ~ 2001, but in 01 Swiss Camp in year 2001. The methods with higher accuracy were selected to correct ERA40 temperature data during the whole period 1958 ~ 2001 to acquire a high precision and long time series temperature data in Greenland ice sheet. And the introduction of Quantile-Mapping method is in this website: http://127.0.0.1:14648/doc/html/Search?objects=1&port=14648.

3.3 Pearson correlation analysis

The Pearson correlation analysis was used to measure the relationship between annual temperature and monthly temperature, and the relationship of monthly temperature between coastal weather stations and inland weather stations.

$$R=\frac{\sum_{i=1}^{n}(X_i-\overline{X})(Y_i-\overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i-\overline{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i-\overline{Y})^2}} \quad (1)$$

where, R represents the Pearson correlation coefficient between X and Y, where 1, -1 and 0 reflect a completely positive correlation, a completely negative correlation and no correlation, respectively, between X and Y. The t-test method was used to determine the significance of the correlation coefficient. $X_i$and $Y_i$reflect the variable values in year i, and$\overline{X}$and $\overline{Y}$are the corresponding mean values.

3.4 Linear Regression equation

In this study, we used linear regression equation to build the relationship between annual temperature and monthly temperature, and the equations were finally used to convert annual temperature into monthly temperature.

$$Y=a+bx+\varepsilon \quad (2)$$

where, Y represents monthly temperature, x represents annual temperature, a is constant, b is

the slope of equation, ε is the random error.

3.5 Model accuracy verification

In this study, we used mean absolute error (MAE), root mean square error (RMSE) and determination coefficient R^2 of validation dataset to evaluate the correction precision of quantile-mapping method.

$$MAE = \left| \frac{\sum_{i=1}^{n} [\hat{Z}(x_i) - Z(x_i)]}{n} \right| \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} [\hat{Z}(x_i) - Z(x_i)]^2}{n}} \quad (4)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n} [\hat{Z}(x_i) - Z(x_i)]^2}{\sum_{i=1}^{n} [Z(x_i) - \bar{Z}(x_i)]^2} \quad (5)$$

where, n represents the numbers of samples in validation dataset, $\hat{Z}(x_i)$ represents the predicted value, $Z(x_i)$ represents the observation value, $\bar{Z}(x_i)$ represent the mean of observation value.

The closer MAE is to 0, the method is unbiased. The smaller RMSE is, the higher prediction accuracy is. The closer the R^2 is to 1, the better the model can explain the dependent variable.

3.6 Time disaggregation method of temperature

The temporal resolution of ice core data is year, we used linear regression equation to convert the annual temperature into monthly temperature.

We firstly analyzed the correlation relationship between annual temperature and monthly temperature, and the correlation relationship between coastal temperature and inland temperature. If the correlation relationship between average annual temperature and monthly temperature is significant, the linear regression equation between average annual temperature and monthly temperature of coastal stations is established. If the correlation relationship between monthly mean temperature of coastal stations and monthly mean temperature of inland stations is significant, the above equation is applied to predict monthly mean temperature of inland stations. We calculated the residuals between predicted temperature of inland stations and the corrected temperature of inland ERA40 data, and we added the residuals when used the linear regression equation, and then we verify the feasibility of the time disaggregation method. If the method is feasible, it is applied to

downscaling analysis of ice core temperature data.

3.7 Construction of spatial distribution pattern of air temperature

ERA5 is a global-scale raster dataset, it's not always accurate when used in a local study area. In this study, we used the coastal temperature observation data and ERA5 temperature data to construct the monthly temperature spatial distribution map. Firstly, we find the location of a coastal weather station in the spatial distribution map of ERA5 data, and the adjacent eight raster point of this location, we regard the mean temperature of ERA5 data of this nine raster points as the coastal temperature, and then we calculated the coefficient between other raster temperature and the mean temperature of this nine rasters, and thirdly, the temperature observation data of DMI coastal stations were substituted and multiplied by the above coefficients to construct the spatial distribution map of temperature.

4. Results and discussion

4.1 Bias correction of ERA40 temperature data in Greenland ice sheet

Fig. 2 shows the accuracy verification results of bias correction. From Fig. 2, we can see that scale method has a bad accuracy in each weather station, it's not suitable for bias correction of ERA40 temperature data, but linear, QUANT-linear, QUANT-tricub, RQUANT-linear, RQUANT-tricub and SSPLIN method has the similar bias correction results, so we calculated the mean temperature of these 6 methods as the final corrected temperature. As seen from Fig. 3, except for 12 NASA-E station, ERA40 temperature data corrected by quantile mapping method basically coincided with the inland observation temperature data, while the performance of 12 NASA-E station was poor, and the corrected ERA40 temperature data was higher than the observation temperature.

Among the 6 methods selected, from the perspective of MAE, 01 Swiss Camp site is between 1.51 ℃ and 1.92℃, 06 Summit site is between 1.37 ℃ and 1.66℃, 07 Tunu-N site is between 1.94 ℃ and 2.16℃, 08 Dye-2 station is between 0 and 2.14℃, and 12 NASA-E station is between 0.97 and 1.11℃. The ERA40 temperature after quantile mapping correction has a small bias from the inland observation temperature, indicating that the corrected data has a certain reliability. From the perspective of RMSE, 01 Swiss Camp site is between 1.99 ℃ and 2.34℃, 06 Summit site is between 1.63 ℃ and 1.96℃, 07 Tunu-N site is between 2.29 ℃ and 2.56℃, 08 Dye-2 station is between

2.47 and 2.51℃, and 12 NASA-E station is between 1.16 and 1.31℃. The relatively small RMSE further illustrates the accuracy of the corrected results. From the perspective of R^2, all 6 methods are above 0.91, indicates that the corrected results have a better accuracy.

From what has been discussed above, we selected 6 methods to correct ERA40 temperature, and the mean temperature of corrected ERA40 was used in this study.

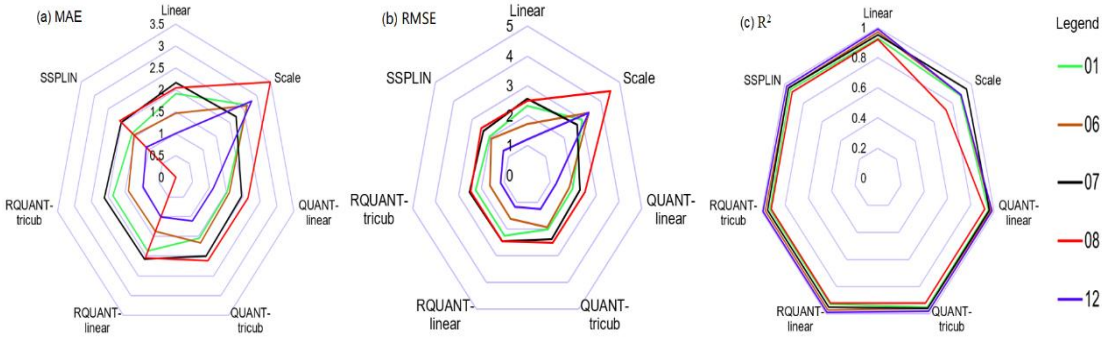


Fig. 2 Accuracy verification results of bias correction

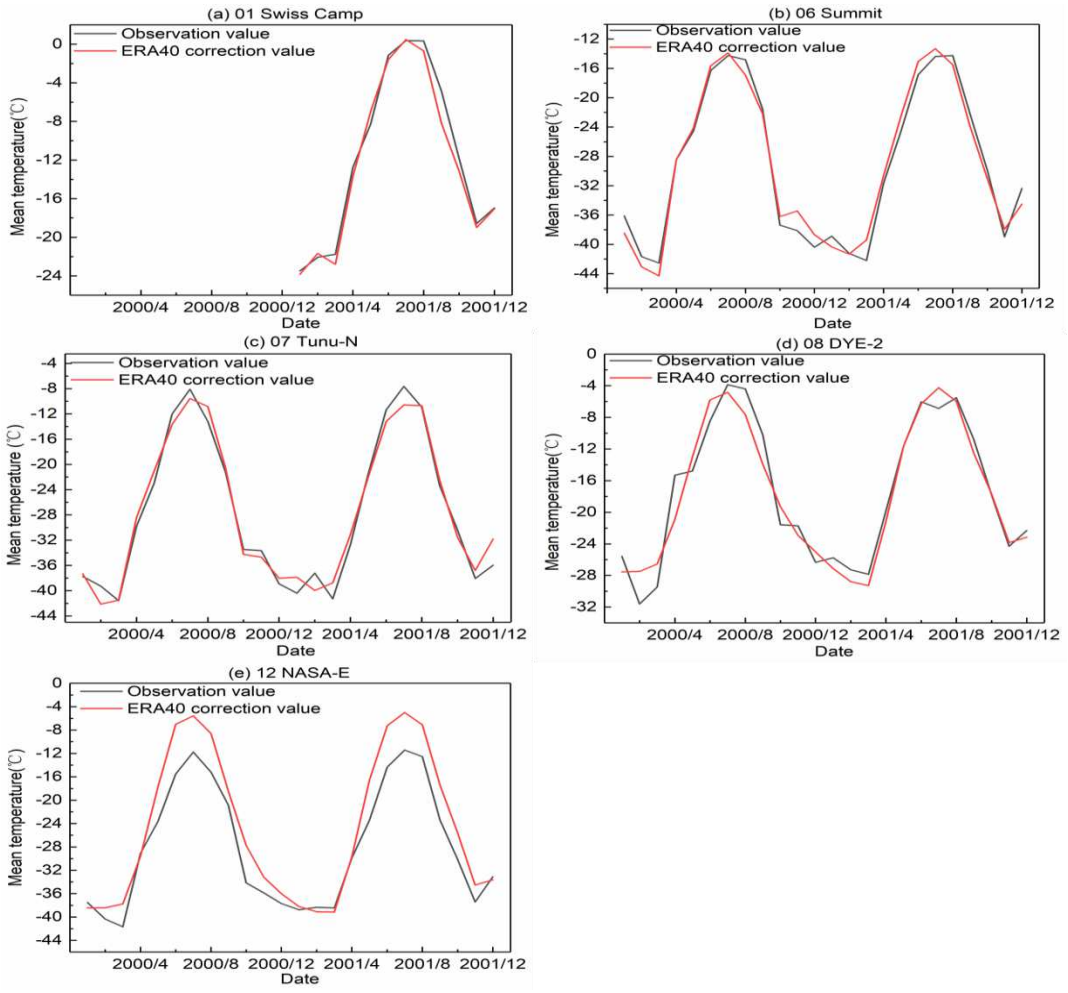


Fig. 3 Comparison between observation temperature and ERA40 correction temperature

4.2 Correlation analysis of Greenland temperature

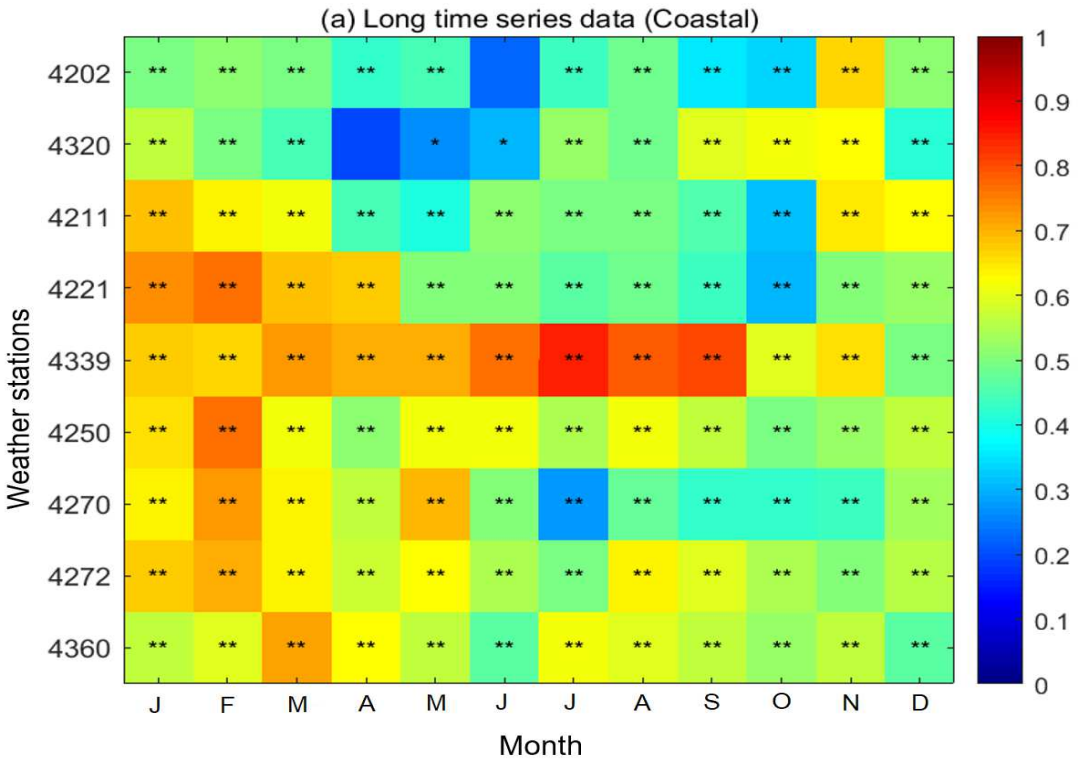
Fig. 4 shows the correlation relationship between annual average temperature and monthly average temperature. As seen from Fig. 4a, annual average temperature and monthly average temperature in coastal weather station are significantly correlated at the 0.01 level, and the correlation coefficients ranged from 0.26 to 0.84. And the correlation coefficients from April to July are lower than that from November to March in most weather stations, except 4339 weather station, indicating that the average annual temperature is more affected by winter temperature fluctuation. As seen from Fig. 4c, the correlation relationship between annual average temperature and summer average temperature is not significant in 01 Swiss Camp, 06 Summit, 07 TUNU-N and 12 NASA-E weather stations, and the annual average temperature are significantly correlated with other months at the 0.01 level or 0.05 level, and the correlation coefficient is above 0.3. As for 08 DYE-2 weather station, the correlation relationship between annual average temperature and April, May and October temperature is not significant, and is significant with temperature of other months.

To discuss the effect of data length between annual average temperature and summer temperature, we also analyzed the correlation relationship between annual average temperature and monthly temperature in long time series data (time span: 1866 ~ 2019) and short time series data (time span: 1958 ~ 2001) in coastal weather stations. As seen from Fig. 4a and Fig. 4b, the correlation relationship may be insignificant from significant when the time span of data is shortened from May to October, which means that the insignificant correlation relationship between annual average temperature and summer temperature is caused by the data length, not data quality.

To reduce the impact of this phenomenon, the regression equation between annual average temperature and monthly temperature of coastal stations was established in the disaggregation analysis of air temperature, and the equation was applied to inland meteorological stations to be adjusted according to residuals, and then the accuracy of disaggregation analysis was further verified. Instead of establishing linear regression equation between average annual temperature and monthly temperature of inland weather stations directly.

Fig. 5 shows the correlation relationship between coastal and inland temperature. In this study, we selected the adjacent coastal weather station that the temperature of which has the highest correlation coefficient with inland temperature, and the linear regression equation between annual

average temperature and monthly temperature of this selected station was used to predicted the monthly temperature of inland weather station, besides, we used residuals to adjust the predicted temperature. As seen from Fig. 5, weather station 4221 is close to weather station 01, and the monthly temperature of these two stations is significantly correlated at the level of 0.05, with the correlation coefficient ranging from 0.55 to 0.82. Therefore, the linear regression equation between annual average temperature and monthly temperature of weather station 4221 was used to predict the monthly temperature of weather station 01. In the same way, 4221, 4320,4360 and 4211 weather stations were selected, and the linear regression equation of them were used to predict the monthly temperature of 08, 12, 07 and 06 weather station, respectively. Besides, we also calculated the average temperature of all coastal weather stations, and the correlation relationship of temperature of inland weather station with it. As seen from Fig. 5, most monthly temperature of inland weather stations has a significantly correlation relationship with the average temperature of all coastal weather stations, and the correlation coefficient is above 0.3. Therefore, in this study, we used both linear regression equation of adjacent coastal weather station and the mean result of all coastal weather stations to predict inland temperature, and methods closer to inland temperature observations were selected for final disaggregation analysis.



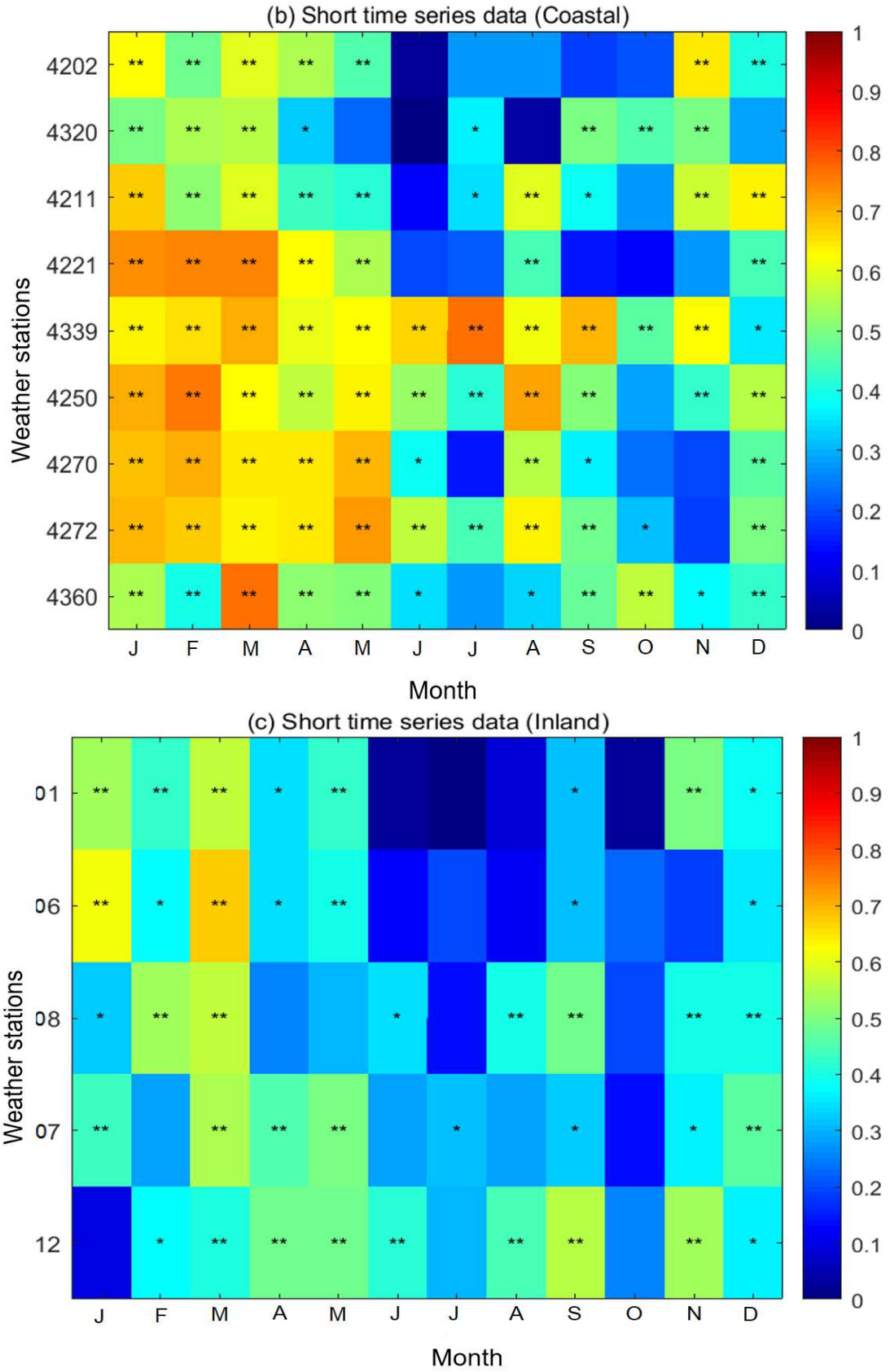


Fig. 4 Correlation relationship between annual average temperature and monthly average temperature. ** and *means that annual temperature and monthly temperature are significantly correlated at 0.01 and 0.05 level, respectively. The longest time series data spans from 1866 to 2019,

and short time series data spans from 1958 to 2001. J, F, M, A, M, J, J, A, S, O, N, D represent the temperature of January to December.

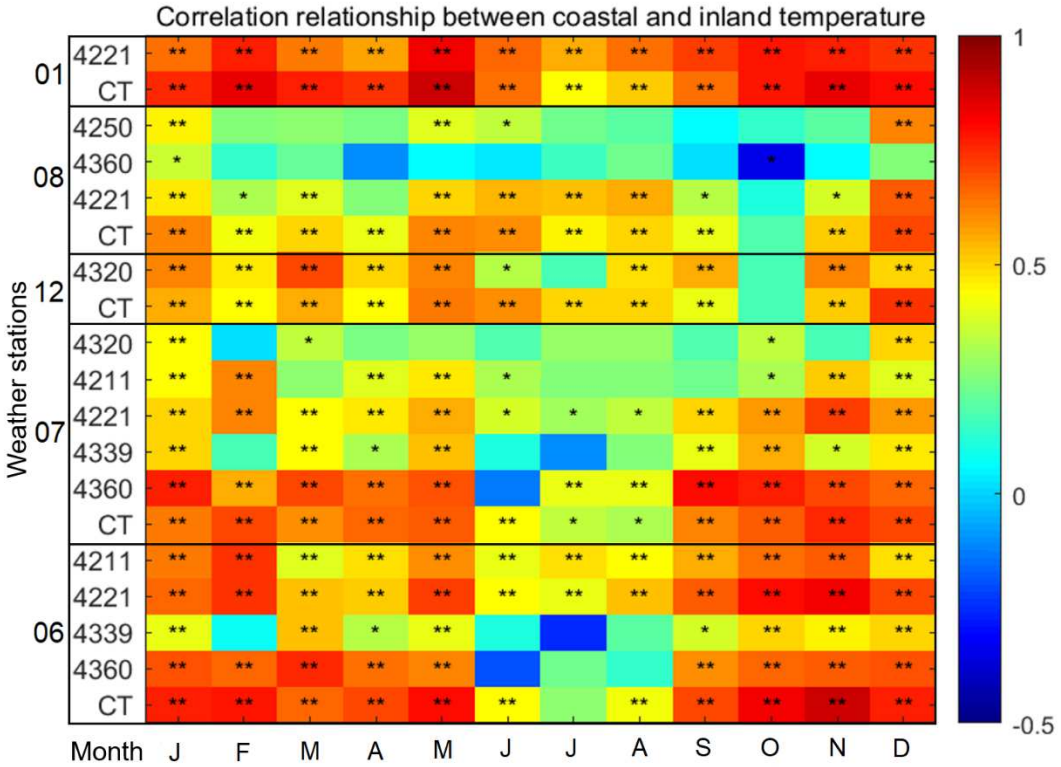


Fig. 5 Correlation relationship between coastal and inland temperature. ** and *means that coastal temperature and inland temperature are significantly correlated at 0.01 and 0.05 level, respectively. CT is the average temperature of coastal weather stations. The column outside and inland of ordinate represents the temperature of inland and coastal stations, respectively.

4.3 Time disaggregation equation of Greenland temperature

Table 2 shows the regression equations between annual average temperature and monthly temperature of coastal weather stations. From Table 2, we can see that all equations were significant at $P<0.001$, and the correlation coefficient R of equations range from 0.15 to 0.77, indicating that the equations can be well used to predict the monthly temperature of coastal weather stations. According to these equations, and the selected adjacent inland weather stations, the monthly temperature of inland weather stations can be predicted, but the predicted results needed to be adjusted by residuals, due to the differences of elevation between coastal and inland weather stations. In this study, we divided the corrected ERA40 temperature into two periods, period year 1971 ~ 2001 (namely, training set) and period year 1958 ~ 1970 (namely, validation set). And the training set was used to calculate the residuals between predicted inland monthly temperature by coastal

linear regression equation and corrected ERA40 monthly temperature data, the validation set was used to verify the accuracy of linear regression equation-residual correction method. In this study, we used the regional residuals not the station residuals. Stations 06, 12 and 07 are divided into a group because they are close to each other, and the median of the residual errors of the three stations was calculated as the residual correction of the monthly predicted temperature in central and northern Greenland. And Station 06 is close to ice core station GISP2, GRIP and NGRIP, Therefore, when downscaling the three ice core temperature data, the residual of 06 Summit site was selected to correct the results of the regression equation. In the southern part of Greenland, 01 and 08 was divided into a group, the median residual was calculated to correct the inland monthly mean temperature predicted by the coastal regression equation.

Table 2 The regression equations between annual average temperature and monthly temperature of coastal weather stations. J, F, M, A, M, J, J, A, S, O, N, D represent the temperature of January to December, respectively, y represents annual average temperature. All equations are significant at $P < 0.001$.

Weather Station	Regression equation	R	Weather Station	Regression equation	R
4221	J=2.09×y-4.95	0.72	4320	J=1.90×y-0.15	0.55
	F=2.54×y-4.13	0.76		F=1.61×y-4.44	0.48
	M=1.82×y-6.22	0.68		M=1.15×y-9.29	0.42
	A=1.34×y-2.49	0.66		A=0.44×y-11.69	0.15
	M=0.57×y+2.83	0.50		M=0.44×y-1.36	0.23
	J=0.47×y+6.81	0.49		J=0.35×y+5.16	0.28
	J=0.33×y+9.00	0.45		J=0.51×y+9.88	0.51
	A=0.35×y+7.75	0.47		A=0.51×y+8.60	0.46
	S=0.36×y+3.91	0.42		S=0.86×y+6.34	0.58
	O=0.34×y-1.93	0.29		O=1.43×y+3.83	0.60
	N=0.70×y-4.48	0.50		N=1.70×y+1.30	0.61
	D=1.09×y-6.07	0.51		D=1.14×y-7.99	0.40
4360	J=1.57×y-5.51	0.57	4211	J=2.21×y-2.33	0.68
	F=1.71×y-5.97	0.58		F=1.97×y-6.18	0.63
	M=1.74×y-4.98	0.70		M=1.49×y-8.39	0.60
	A=1.21×y-2.08	0.61		A=0.81×y-6.80	0.43
	M=0.69×y+2.02	0.56		M=0.52×y+0.70	0.39
	J=0.42×y+5.31	0.45		J=0.51×y+5.52	0.51
	J=0.57×y+7.51	0.60		J=0.50×y+8.80	0.49
	A=0.52×y+6.91	0.58		A=0.48×y+8.42	0.49
	S=0.64×y+4.29	0.56		S=0.35×y+3.73	0.44
	O=0.81×y+0.32	0.51		O=0.32×y-1.57	0.30
	N=1.07×y-2.87	0.56		N=1.08×y-0.78	0.63
	D=1.05×y-4.96	0.45		D=1.74×y-1.27	0.62

	J=1.86×y-4.88	0.69
	F=1.95×y-5.43	0.69
	M=1.61×y-6.18	0.70
	A=0.88×y-3.75	0.58
	M=0.71×y+2.34	0.63
CT	J=0.53×y+6.16	0.59
	J=0.48×y+8.44	0.52
	A=0.67×y+8.63	0.77
	S=0.48×y+4.15	0.56
	O=0.63×y-0.53	0.50
	N=0.87×y-3.87	0.56
	D=1.34×y-5.09	0.58

4.4 Accuracy verification of Greenland monthly temperature disaggregation result

Fig. 6 shows the accuracy of time disaggregation result in inland weather stations. From the perspective of MAE during period from 1971 to 2001(Fig. 6a), the MAE of 01 Swiss Camp, 08 Dye-2 and 06 Summit sites was the smallest in July, which gradually decreased from January to July and increased from July to December. However, MAE at 12 NASA-E and 07 TUNU-N sites did not show an obvious change pattern, and the MAE of these 5 sites ranges from 0.58 to 4.66℃. The MAE in 12 NASA-E is larger, it may be related to the poor bias correction results of 12 NASA-E sites (Fig. 3), with MAE around 3℃ at other sites. From the perspective of RMSE (Fig. 6c), which has a similar change pattern with MAE, the RMSE of 01 Swiss Camp, 08 Dye-2 and 06 Summit weather stations was the smallest in July, which gradually decreased from January to July and increased from July to December. However, RMSE at 12 NASA-E and 07 TUNU-N sites did not show an obvious change pattern, and RMSE in these 5 weather stations ranges from 0.76 ~ 5.04 ℃. Because the poor bias correction of 12 NASA-E, the RMSE in 12 NASA-E station is the largest. From the perspective of R (Fig. 6e), the prediction of temperature in Winter is better than that in Summer, and R in these 5 weather stations range from 0.01 to 0.64, R in some months is very smaller, this is in normal. Because we used the regional residuals to adjust the inland prediction of monthly temperature not the residuals of one weather station when we used the coastal linear regression equation between annual average temperature and monthly temperature, leading to a lower R.

We selected the data set during period 1958 ~ 1970 to validate the accuracy of linear regression equation-residual correction method. From Fig. 6b, Fig. 6d, Fig. 6f, we can see that the accuracy is lower than period 1971 ~ 2001. As shown from Fig. 6b, MAE in 5 weather stations ranges from

0.57 to 4.86 ℃, and MAE in 12 NASA-E is poor, too. MAE is larger from October to March than that from April to September, indicating that the accuracy of linear regression equation-residual correction method is better in Summer than Winter. As shown from Fig. 6d, RMSE in 5 weather stations range from 0.71 to 5.28 ℃. And RMSE has a similar change pattern with MAE, which is larger from October to March than that from April to September. As shown from Fig. 6f, R in 5 weather stations ranges from -0.23 to 0.84, which is similar with R during period 1971 ~ 2001. But there are some negative values of R, this may be affected by regional residuals, which needed to be improved in future work. From the accuracy of validation set, linear regression equation-residual correction method can be well used in Greenland to predict monthly temperature of inland weather stations. In the next analysis, we used the linear regression between annual average temperature and monthly temperature of coastal weather stations to predict monthly temperature of ice cores in Greenland ice sheet, and residuals correction method was used to acquire accurate results.

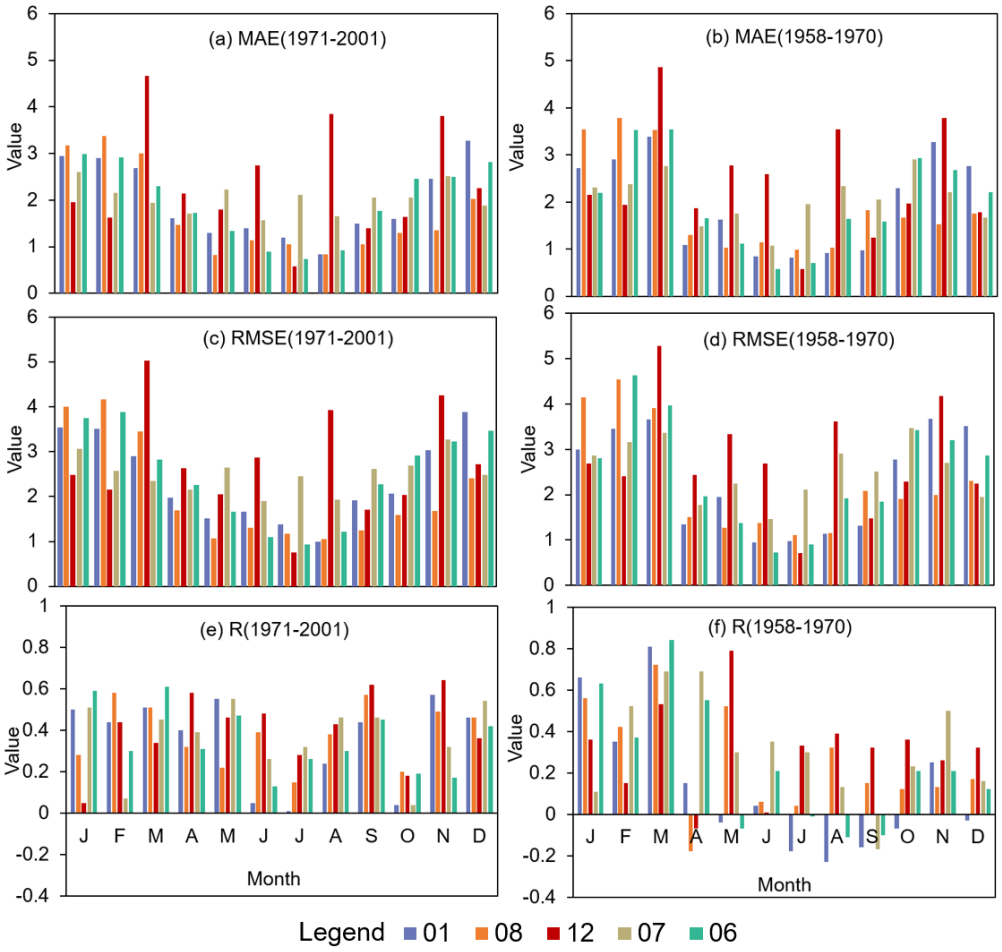


Fig. 6 Accuracy verification of disaggregation result in inland weather stations

392 **4.5 Comparison with other temperature reconstruction results**

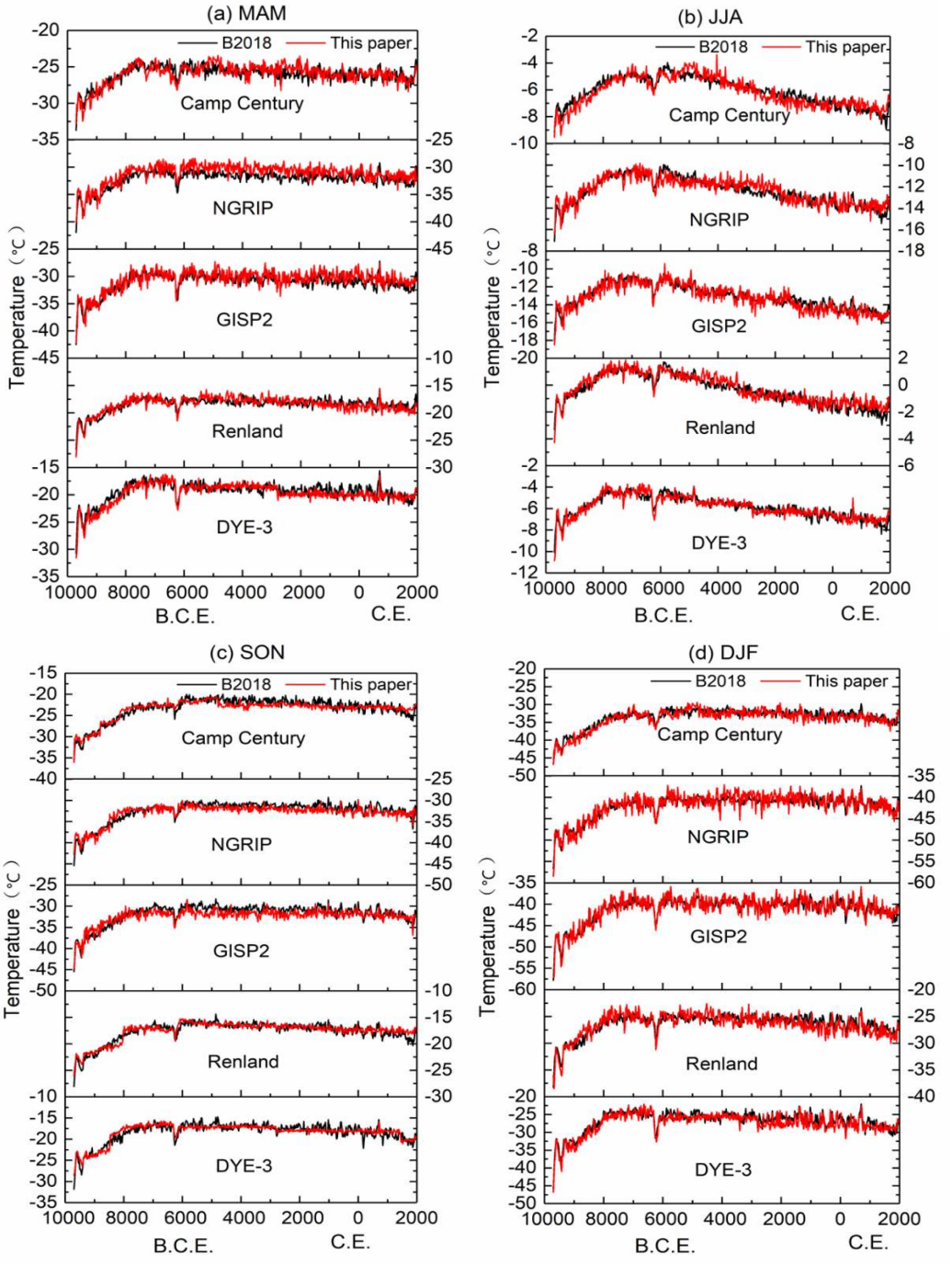
393 In this study, we used linear regression equation- residuals correction method to reconstruct
394 the monthly temperature of Greenlad ice core data. The bias of reconstructed monthly temperature
395 between our results and Buizert's results (2018)is less than 3 ℃.

396 Buizert (2018) used temperature proxy index N^{15} to reconstruct average annual temperature of
397 ice core data, and the reconstructed error of average annual temperature of NGRIP, GISP2 and
398 NEEM ice core is about 3 ℃, and the error in Holocene is 1.5℃. And they used meteorological
399 observation data combing with regional climate modeling method to reconstruct seasonal
400 temperature, and the error of reconstructed seasonal temperature ranges from 1.4 to 2 ℃.

401 As seen from Fig. 7, there exists about 3 ℃ bias between our results and Buizert's rusult due
402 to the use of different temperature proxy index and different temperature reconstructing method.
403 But both results can describe temperature change characteristic over past 10 000 years, such as the
404 temperature change characteristic in Little Ice Age, Holocene Thermal Maximum, 8.2 ka event and
405 11.3 ka event.

406 As seen from Fig. 7,the Little Ice Age, 8.2 ka and 11.3 ka events were three Holocene cooling
407 events. The Little Ice Age event occurred during period 1820 C.E. ~ 860 C.E., and the minimum
408 average annual temperature of Camp Century, NGRIP, GRIP, GISP2, Renland and DYE-3 is -
409 24.94 ℃, -33.08 ℃, -31.24 ℃, -31.69 ℃, -18.43 ℃ and -19.55 ℃, respectively. And the minimum
410 monthly temperature of these 6 ice cores is -38.49 ℃, -47.22 ℃,-47.23 ℃, -46.64 ℃, -32.29 ℃,and
411 -33.28 ℃, respectively.8.2 ka event occurred during period 6220 B.C.E. ~ 6260 B.C.E., and the
412 minimum average annual temperature of Camp Century, NGRIP, GRIP, GISP2, Renland and DYE-
413 3 is -23.36 ℃, -31.90 ℃, -32.52 ℃, -33.42 ℃, -17.94 ℃ and -20.58 ℃, respectively, and the
414 minimum monthly temperature of these 6 ice cores is -38.66 ℃, -47.94 ℃, -48.26 ℃, -48.01 ℃, -
415 33.34 ℃ and -35.47 ℃, respectively. 11.3 ka event occurred during period 9400 B.C.E. ~ 9480
416 B.C.E., and the minimum average annual temperature of Camp Century, NGRIP, GRIP, GISP2,
417 Renland and DYE-3 is -30.15 ℃, -38.24 ℃, -33.93 ℃, -38.02 ℃, -20.81 ℃, and -25.39 ℃,
418 respectively. And the minimum monthly temperature of these 6 ice cores is -44.79 ℃, -55.12 ℃, -
419 55.84 ℃, -57.70 ℃, -38.93 ℃ and -44.87 ℃, respectively. Holocene Thermal Maximum was a
420 period of high temperature, and the average annual temperature of Camp Century, NGRIP, GRIP,

GISP2, Renland and DYE-3 is -21.62 ℃, -28.97 ℃, -29.10 ℃, -28.69 ℃, -14.80 ℃ and -16.43 ℃, respectively.



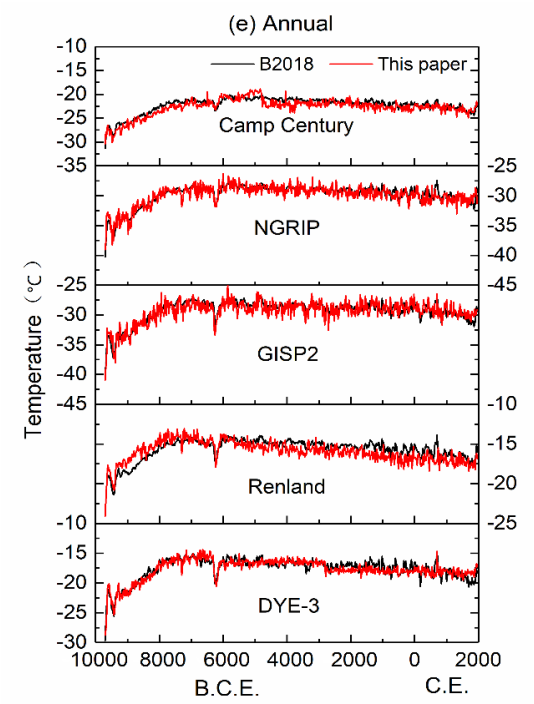


Fig. 7 Comparison between reconstructed temperature in this study and Buizert (2018). B2018 represents the reconstructed temperature of Buizert, 2108.

4.6 The spatial distribution pattern of Greenland monthly temperature

In this study, we uesed coastal meteorological observation data and ice core data combing with ERA5 data to construct the temperature spatial distribution map of Greenland. As seen from Fig. 8, the spatial distribution characteristic of temperature in Greenland has obvious elevation effect,that is, the temperature decreases gradually with the increase of elevation.The temperature increases gradually from the north to the southregion.And temperature decreases gradually from the east to the west region from November to April, while the temperature change from May to October is opposite to that from November to April. The monthly average temperature of the whole island is -22.63℃ (January), -23.22℃ (February), -23.45℃ (March), -18.04℃ (April), -10.79℃ (May), -5.24℃ (June), -2.87℃ (July), -4.68℃ (August), -10.38℃ (September), and -15.82℃ (October), -19.20℃ (November) and -21.76℃ (December), respectively. The results of temperature construction in this study are in good agreement with the spatial distribution of temperature constructed by Fausto et al. (2009).

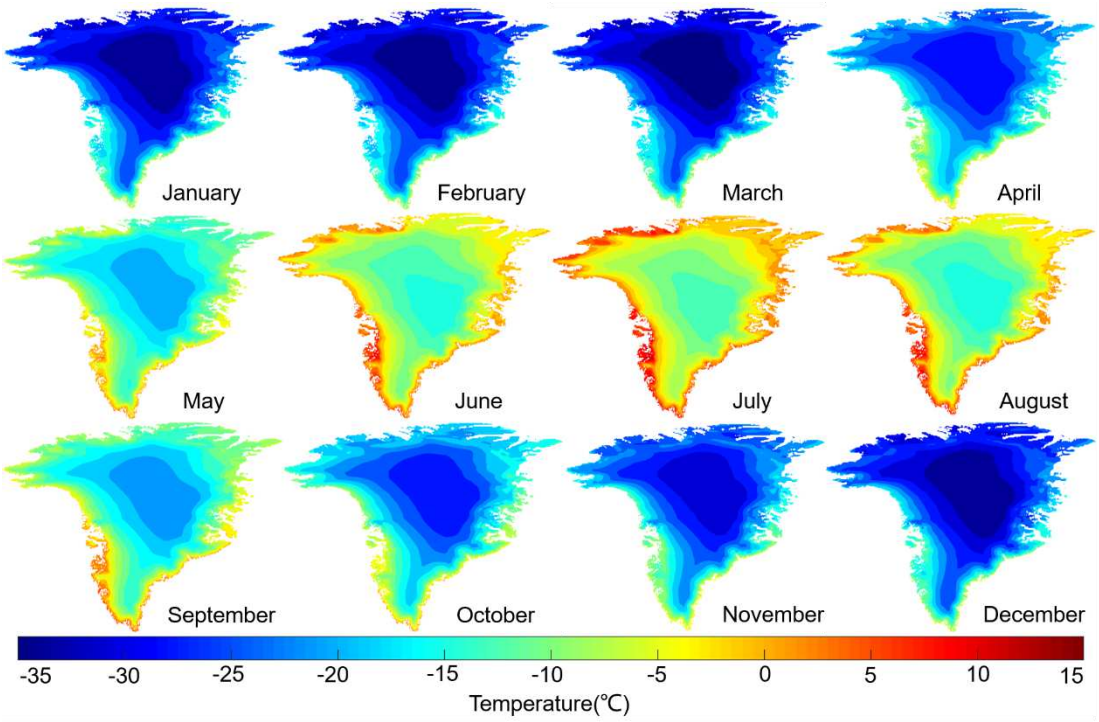


Fig. 8 Spatial distribution map of average Greenland monthly temperature during period 1961-2019

4.7 Verify the accuracy of monthly temperature spatial distribution map

In order to verify the accuracy of monthly temperature spatial distribution map of Greenland, ERA5 temperature data from 1981 to 2010 were selected for modeling, and data from 2011 to 2020 were used for verification, and evaluation methods of R, MAE and RMSE were selected to verify the feasibility.

As seen from Fig. 9, monthly correlation coefficient R of the island is between 0.54 ~ 0.77, among them, some regions of R is negative, these value are in the northern, northeastern and east-central region of the island, because there are little weather stations in these regions. From the respective of MAE, the average MAE of the island is between 0.76 ~ 2.07℃, it means that the bias between predicted temperature and observation temperature is lower, the predicted temperature map has higher accuracy. From the spatial distribution map of MAE, the higher bias is in the regions of higher altitudes, because of sparse weather stations. From the respective of RMSE, the average RMSE of the between 0.92 ~ 2.64℃, it means that the predicted temperature map has higher accuracy.

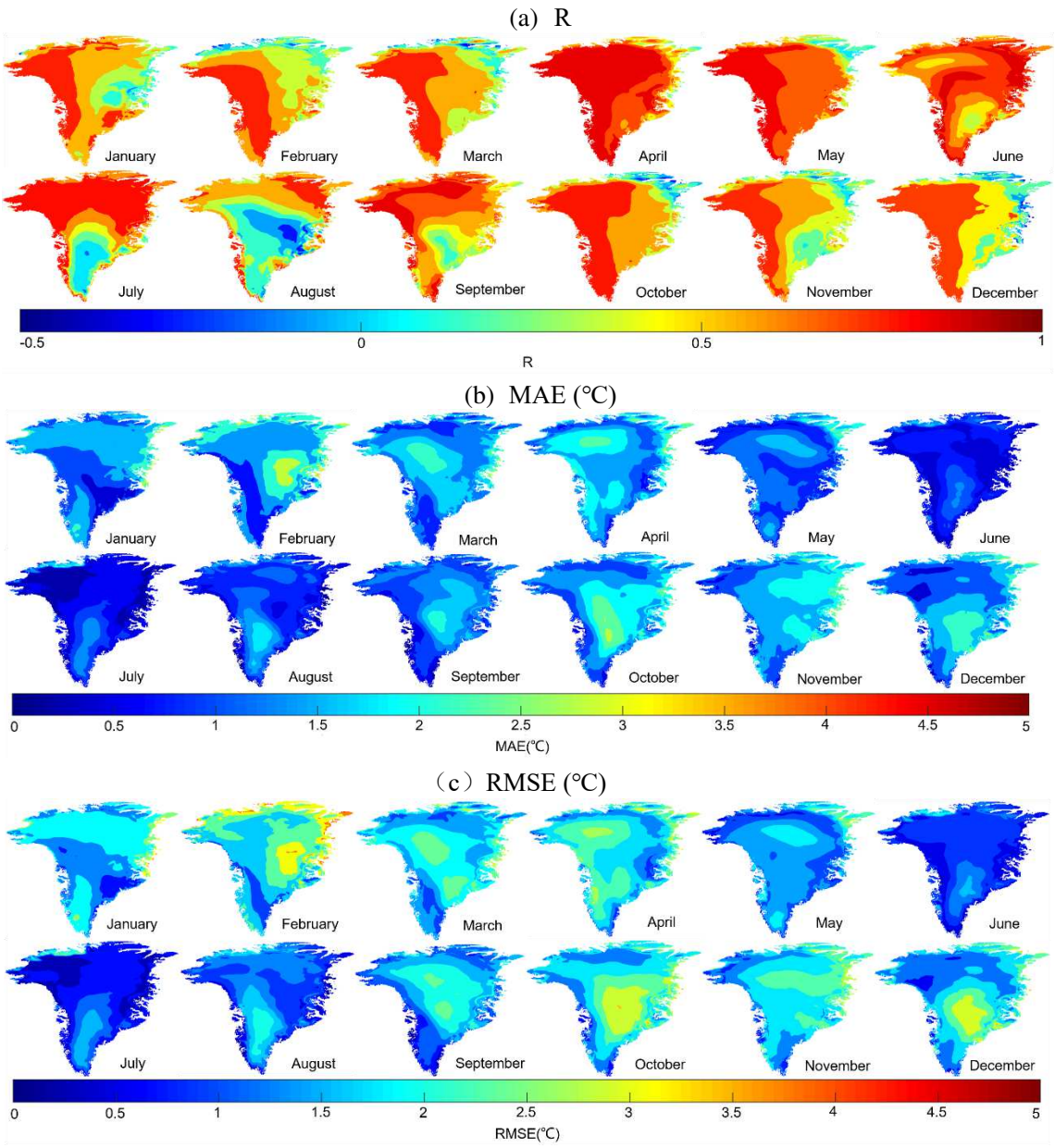


Fig. 9 Verify the accuracy of spatial distribution map of monthly temperature

From what has been discussed above, the average bias of predicted temperature spatial distribution map of the island is about 2 ℃, which has higher predicted accuracy. And the predicted accuracy in the higher altitudes is lower because of spare weather stations.

4.8 The temporal variation characteristic of reconstructed monthly temperature

In order to analyze the variation characteristics of air temperature from 9700 B.C.E. to 2019 C.E., according to the spatial distribution map of air temperature constructed above, air temperature is greatly affected by elevation. This paper divides the study area into four sub-regions according to elevation. That is, the elevation of 9 ~ 1 000, 1 000 ~ 2 000, 2 000 ~ 3 000 and 3 000 ~ 3 673 m, respectively, and the temporal variation characteristics of monthly temperature were analysed.

As seen from Fig. 10, from 9700 B.C.E. to 2019 C.E., the air temperature from September to May of the next year showed a significant increasing trend at the 0.05 level, while the air temperature from June to August showed a significant decreasing trend at the 0.05 level. During the whole period, the temperature change can be divided into 9 periods. Table 3 lists the slope of temperature change for each period. As seen from Fig. 10 and Table 3, from 9700 B.C.E. to 9600 B.C.E., the temperature in each elevation region showed an obvious upward trend, and the temperature rising rate in this period was the most obvious among all periods. From 9600 B.C.E. to 9400 B.C.E., the temperature at all elevation regions showed a decreasing trend, which was consistent with the cooling event time of 11.3 ka. Then, from 9400 B.C.E. to 7720 B.C.E., the temperature gradually increased until 7720 B.C.E. to 6340 B.C.E., the temperature remained almost constant or showed a slight decreasing trend.8.2 ka event (6340 B.C.E. ~ 6240 B.C.E.) was the most severe cooling event in the last 10 000 years. Then, from 6240 B.C.E. TO 6000 B.C.E., the temperature began to rise gradually. From 6000 B.C.E. to 1800 C.E., the temperature showed a decreasing trend. From 1800 C.E. to 2019 C.E., the temperature showed an upward trend. And the slope difference of temperature change in the same period and month in different elevation areas is not obvious. The reconstructed in our study is consist with previous work (Badgeley et al., 2020; Polyakov et al., 2002; McKay et al., 2014; Buizert et al., 2018; Kobashi et al., 2017), indicating that the reconstructed temperature of our study has high reliability.

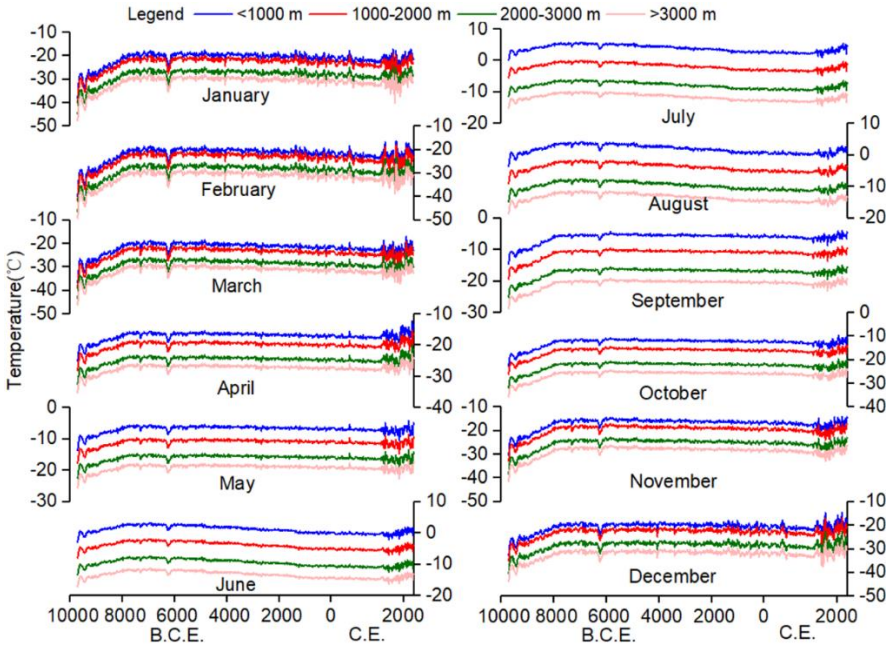


Fig. 10 Temporal variation characteristic of monthly temperature over past 10,000 years.

Table 3 The slope of temperature change during different periods (℃ per two decades). Region 1 ~ 4 represent elevation region 9 ~ 1000 m, 1000 ~ 2000 m, 2000 ~ 3000 m and 3000 ~ 3673 m, respectively. The minus sign represents B.C.E., and the unmarked sign represents C.E.

Reg.	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	-9700~2019	0.0056	0.0058	0.0034	0.0021	0.0018	-0.0040	-0.0040	-0.0037	0.0039	0.0043	0.0051	0.0040
	1800~ 2019	0.1622	0.1725	0.0503	0.1344	0.0120	0.0541	0.0997	0.0804	0.0785	0.0618	0.0751	0.2198
	-6000~1800	-0.0072	-0.0077	-0.0075	-0.0036	-0.0028	-0.0086	-0.0084	-0.0094	-0.0028	-0.0036	-0.0053	-0.0044
1	-6240~-6000	0.5421	0.5748	0.4972	0.2591	0.2154	0.1630	0.1481	0.2078	0.1665	0.2172	0.3334	0.3704
	-6340~-6240	-1.2985	-1.3715	-1.1384	-0.6098	-0.5156	-0.3861	-0.3540	-0.4860	-0.3513	-0.4642	-0.7317	-0.9162
	-7720~-6340	0.0000	0.0000	0.0000	-0.0032	-0.0038	0.0000	0.0000	0.0000	0.0019	0.0025	0.0036	-0.0029
	-9400~-7720	0.1184	0.1252	0.1051	0.0561	0.0473	0.0357	0.0327	0.0450	0.0702	0.0809	0.1053	0.0830
	-9600~-9400	-0.6502	-0.6876	-0.6158	-0.3446	-0.2962	-0.1977	-0.1813	-0.2489	-0.1544	-0.2121	-0.3487	-0.4545
	-9700~-9600	2.2247	2.3614	2.1466	1.1504	0.9693	0.7258	0.6644	0.9137	0.7558	0.9684	1.4598	1.5063
	-9700~2019	0.0056	0.0058	0.0034	0.0020	0.0017	-0.0039	-0.0039	-0.0036	0.0039	0.0042	0.0050	0.0046
	1800~ 2019	0.1602	0.1708	0.0494	0.1332	0.0119	0.0531	0.0976	0.0788	0.0770	0.0609	0.0743	0.2178
	-6000~1800	-0.0072	-0.0077	-0.0074	-0.0036	-0.0028	-0.0085	-0.0082	-0.0092	-0.0027	-0.0036	-0.0053	-0.0044
2	-6240~-6000	0.5378	0.5704	0.4929	0.2562	0.2120	0.1599	0.1451	0.2035	0.1634	0.2141	0.3298	0.3670
	-6340~-6240	-1.2883	-1.3610	-1.1286	-0.6029	-0.5074	-0.3789	-0.3467	-0.4759	-0.3447	-0.4576	-0.7239	-0.9078
	-7720~-6340	0.0000	0.0000	0.0000	-0.0032	-0.0038	0.0000	0.0000	0.0000	0.0018	0.0025	0.0035	-0.0028
	-9400~-7720	0.1175	0.1242	0.1042	0.0555	0.0465	0.0351	0.0320	0.0440	0.0689	0.0797	0.1042	0.0823
	-9600~-9400	-0.6452	-0.6824	-0.6105	-0.3406	-0.2915	-0.1941	-0.1775	-0.2438	-0.1515	-0.2090	-0.3450	-0.4503
	-9700~-9600	2.2073	2.3435	2.1281	1.1374	0.9540	0.7123	0.6507	0.8947	0.7416	0.9547	1.4443	1.4925
	-9700~2019	0.0055	0.0057	0.0033	0.0020	0.0017	-0.0038	-0.0038	-0.0035	0.0038	0.0041	0.0049	0.0045
	1800~ 2019	0.1549	0.1664	0.0475	0.1313	0.0116	0.0520	0.0954	0.0770	0.0753	0.0595	0.0726	0.2129
	-6000~1800	-0.0070	-0.0075	-0.0073	-0.0035	-0.0027	-0.0083	-0.0080	-0.0090	-0.0027	-0.0035	-0.0052	-0.0043
3	-6240~-6000	0.5267	0.5588	0.4831	0.2514	0.2080	0.1567	0.1419	0.1990	0.1596	0.2090	0.3224	0.3588
	-6340~-6240	-1.2617	-1.3333	-1.1062	-0.5917	-0.4978	-0.3711	-0.3390	-0.4655	-0.3368	-0.4466	-0.7076	-0.8876
	-7720~-6340	0.0000	0.0000	0.0000	-0.0031	-0.0037	0.0000	0.0000	0.0000	0.0018	0.0024	0.0034	-0.0028
	-9400~-7720	0.1151	0.1217	0.1022	0.0545	0.0456	0.0343	0.0313	0.0431	0.0674	0.0778	0.1018	0.0804

	-9600~-9400	-0.6318	-0.6685	-0.5984	-0.3343	-0.2860	-0.1901	-0.1736	-0.2384	-0.1480	-0.2041	-0.3372	-0.4403
	-9700~-9600	2.1616	2.2957	2.0860	1.1162	0.9359	0.6978	0.6362	0.8751	0.7247	0.9319	1.4117	1.4592
4	-9700~2019	0.0054	0.0056	0.0033	0.0020	0.0017	-0.0037	-0.0038	-0.0035	0.0037	0.0040	0.0049	0.0044
	1800~ 2019	0.1520	0.1640	0.0465	0.1302	0.0115	0.0512	0.0941	0.0760	0.0742	0.0586	0.0716	0.2098
	-6000~1800	-0.0069	-0.0074	-0.0072	-0.0035	-0.0027	-0.0082	-0.0079	-0.0089	-0.0026	-0.0034	-0.0051	-0.0042
	-6240~-6000	0.5205	0.5525	0.4779	0.2487	0.2054	0.1544	0.1399	0.1962	0.1574	0.2059	0.3182	0.3536
	-6340~-6240	-1.2469	-1.3184	-1.0943	-0.5853	-0.4917	-0.3657	-0.3343	-0.4590	-0.3321	-0.4400	-0.6983	-0.8746
	-7720~-6340	0.0000	0.0000	0.0000	-0.0031	-0.0037	0.0000	0.0000	0.0000	0.0018	0.0024	0.0034	-0.0027
	-9400~-7720	0.1137	0.1203	0.1011	0.0539	0.0451	0.0338	0.0309	0.0425	0.0664	0.0767	0.1005	0.0793
	-9600~-9400	-0.6244	-0.6610	-0.5920	-0.3307	-0.2825	-0.1873	-0.1712	-0.2351	-0.1460	-0.2010	-0.3328	-0.4338
	-9700~-9600	2.1363	2.2700	2.0635	1.1042	0.9244	0.6876	0.6273	0.8628	0.7145	0.9181	1.3932	1.4379

4.9 Discussion

Due to the limitations of data and methods, there are some errors in the reconstruction of monthly temperature in Greenland. The possible error sources mainly include the following three aspects: the error of converting ice core proxy indicator into actual temperature, the error of constructing spatial distribution map of temperature, and the downscaling error of temperature.

$\delta^{18}O$ is usually used as a temperature proxy to analyze the characteristics of temperature changes in Greenland during the past ten thousand years. The $\delta^{18}O$ is converted into the actual temperature by using the conversion function method. There exits deviation between the converted temperature value and the real temperature value, which cannot be measured at present. The temperature deviation between the converted temperature and Buizert temperature in this study is within 3℃. In addition, $\delta^{18}O$ can produce some errors during laboratory measurements (Vinther et al., 2006; Stuiver and Grootes, 2000), this paper ignores this error.

In order to analyze the spatial variation characteristics of air temperature in Greenland, we constructed a spatial distribution map based on the spatial distribution characteristics of ERA5 air temperature in Greenland, and substituted the data of coastal meteorological stations and ice cores. According to the accuracy verification results, the average monthly MAE of the temperature spatial distribution map of the whole island is between 0.76 ℃ and 2.07℃.

The downscaling method of temperature was adopted by linear regression equation - residual correction method. Among this, the deviation between the temperature reconstructed by this method and the reconstructed temperature by Buizert is within 3℃.

Due to the lack of real temperature data, quantitative analysis of reconstruction errors of temperature and precipitation in Greenland is a difficult problem. This paper makes a simple comparison based on existing literature, which can be strengthened in future studies.

5. Conclusions

Polar climate change and its influence on sea level and sea ice has been a hot topic in recent years. We took Greenland as a study area in this study, reconstructed the monthly temperature dataset over past 10,000 years, and analyzed the monthly temperature change characteristic of Greenland. And from the reconstructed results, we can make the following conclusions:

The temperature of September to May showed a significant increasing trend at the 0.05 level

during period 9700 B. C. E. ~ 2019 C.E., and the increasing rate is 0.0017 ~ 0.0058 ℃ every two decades. However, the temperature of June to August showed a significant decreasing trend, and the decreasing rate is -0.0035 ~ -0.0040 ℃ every two decades. But the reconstructed results exist 3 ℃ bias compared with Buizert's reconstructed results. In the future, data assimilation method can be used to reduce the uncertainty of the reconstruction results in combination with the climate model simulation data.

Acknowledgments

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Data Availability Statement

The monthly coastal meteorological observation data in Greenland was downloaded from Danish Meteorological Institute (DMI), and the website is: https://www.dmi.dk/publikationer/. The ice cores data were downloaded from NOAA paleoclimatology data website, and the website is: https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets. And the ERA40 and ERA5 data were downloaded from the following website: https://apps.ecmwf.int/datasets/data/era40-mnth/levtype=sfc/ and https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means?tab=overview.

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