Journal of Global Change Data & Discovery. 2022, 6(3): 366-373
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Global Change Research Data Publishing & Repository

# Reconstructed Arctic Summer Sea Ice Areal Extent over the Past Millennium

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**Abstract:** Arctic sea ice is an important component of the Earth system. Changes in sea ice are critical to the climate of polar regions and, by extension, the mid-latitudes (North America, Eurasia, etc.). Remote sensing observations over the last 30 years have revealed that Arctic sea ice is melting rapidly, and it remains unclear whether this trend exceeds historical sea ice fluctuations. Resolving this uncertainty requires reconstructing a longer time series of Arctic sea ice variability. Many studies have attempted to reconstruct sea ice extent or sea ice density using proxy indicators. However, these studies mostly reflect changes in local ice coverage and lack information on broader Arctic sea ice variability. Using the high albedo of Arctic sea ice, we developed a statistical model of sea ice albedo-atmospheric circulation in order to reconstruct the spatial and temporal changes in Arctic summer sea ice areal extent over the past millennium. The results show that the spatial and temporal dynamics of the summer Arctic sea ice areal extent modelled by this method are in strong agreement with remote sensing observations. The reconstructed sea ice record shows that the rapid trend in ice melt over the last 30 years greatly exceeds historical fluctuations of sea ice area. This sea ice reconstruction method establishes the foundation for additional reconstructions of longer-term sea ice changes in the historical period. Furthermore, this reconstruction shows that the maximum ice coverage occurred in 1259 and encompassed an area of approximately 8.7 million $km^2$, while the minimum occurred in 2003 and covered approximately 5.38 million $km^2$. The difference between the minimum and maximum of Arctic sea ice areal extent is approximately 3.32 million $km^2$, which is equivalent to a 38% reduction in coverage since peak extent occurred over 700 years ago.

**Keywords: Arctic region; summer; sea ice area; sea ice albedo-atmospheric circulation model**

**DOI:** https://doi.org/10.3974/geodp.2022.03.06

**CSTR:** https://cstr.escience.org.cn/CSTR:20146.14.2022.03.06

**Dataset Availability Statement:**

The dataset supporting this paper was published and is accessible through the *Digital Journal of Global Change Data Repository* at: https://doi.org/10.3974/geodb.2022.05.01.V1 or https://cstr.escience.org.cn/CSTR:20146.11.2022.05.01.V1.

**Received:** 05-12-2022; **Accepted:** 07-11-2022; **Published:** 25-09-2022

**Foundation:** Ministry of Science and Technology of P. R. China (2017YFA0603303)

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**Data Citation:** [1] Ren, S., Guo, H. Reconstructed Arctic summer sea ice areal extent over the past millennium [J]. *Journal of Global Change Data & Discovery*, 2022, 6(3): 366–373. https://doi.org/10.3974/geodp.2022.03.06. https://cstr.escience.org.cn/CSTR:20146.14.2022.03.06.

[2] Ren, S., Guo, H. Reconstructed dataset of Arctic summer sea ice area (850–2005) [J/DB/OL]. *Digital Journal of Global Change Data Repository*, 2022. https://doi.org/10.3974/geodb.2022.05.01.V1. https://cstr.escience.org.cn/CSTR:20146.11.2022.05.01.V1.

# 1 Introduction

Arctic sea ice is an important component of the Earth system. Because of its high albedo, changes in the areal extent of Arctic sea ice directly affect the energy balance in the Arctic region, which can impact the Arctic climate via positive feedbacks[1]. Furthermore, changes in the regional energy balance also affect larger circulation systems, such as the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO), which may greatly influence the climate in the mid-latitudes (e.g., North America and Eurasia)[2–4]. Remote sensing observations show a significant decreasing trend in Arctic sea ice coverage over the past 30 years. Notably, the area of sea ice in September has been declining at a rate of 12.4% per decade and by the end of 2012 was reduced to nearly half of its maximum area[5–7]. However, it remains unclear whether this trend exceeds the historical rate of sea ice change. Numerous previous studies have attempted to answer this question by reconstructing past Arctic sea ice variability. For example, Walsh *et al.* (2001)[8] reconstructed sea ice areal changes in the Chukchi Sea from 1953 to 2007 using instrumental measurements; de Vernal *et al.* (2008)[9] reconstructed sea ice coverage in the Chukchi Sea from 1327–1952 based on sporulation data; Bonnet *et al.* (2010)[10] used marine sediment data to reconstruct sea ice areal extent in the Fram Strait from 579–1943. These proxy indicators may sufficiently reflect long term temporal changes in sea ice area or sea ice density within a region but they lack information regarding broader sea ice changes throughout the Arctic. Considering these limitations, this study explores a new method for reconstructing past sea ice areal extent. Additionally, this work presents a reconstruction of Arctic sea ice coverage from 850–2005 A.D. using a statistical model of sea ice albedo-atmospheric circulation based on the high albedo of Arctic sea ice. The sea ice area described in this paper refers to the size of the area corresponding to the sea ice extent, which has the same meaning as the sea ice extent indicator of remote sensing observation.

# 2 Metadata of the Dataset

The metadata of Reconstructed dataset of Arctic summer sea ice area (850–2005)[11] is summarized in Table 1. It includes the dataset full name, short name, authors, year of the dataset, temporal resolution, spatial resolution, data format, data size, data files, data publisher, and data sharing policy, etc.

# 3 Methods

## 3.1 Model Development

Arctic sea ice variability is influenced not only by the near-surface temperature in the Arctic Ocean region, but also by circulation driven changes to the energy transfer from the middle and low latitudes to the high latitudes. These changes also affect interannual ice fluctuations. In addition, Arctic sea ice area is spatially variable, and sea ice in different regions is controlled by different regional climate systems. To accurately simulate the spatial and temporal variability of sea ice, sea ice albedo is chosen to characterize sea ice areal variability, global sea level pressure is used as an indicator reflective of global circulation changes in other regions, and the statistical relationship between Arctic sea ice albedo and distal sea level pressures is modelled at each grid cell using the empirical statistical model (Lasso) method. The Lasso method is based on the assumption of sparsity among higher-dimensional variables, and can effectively compress

**Table 1** Metadata summary of the Reconstructed dataset of Arctic summer sea ice area (850–2005)

| Items | Description |
|---|---|
| Dataset full name | Reconstructed dataset of Arctic summer sea ice area (850–2005) |
| Dataset short name | ArcticSeaIceArea850-2005 |
| Authors | Ren, S. 0000-0002-6190-755X, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, shuairen@itpcas.ac.cn<br>Guo, H. 0000-0002-4333-6167, State Key Laboratory of Hydroscience and Engineering, Department of Hydraulic Engineering, Tsinghua University |
| Year | 850–2005 A.D. |
| Temporal resolution | Year |
| Data format | .xlsx |
| Data size | 1.01 MB (Compressed to one single file with 684 KB) |
| Data publisher | Global Change Research Data Publishing & Repository, http://www.geodoi.ac.cn |
| Address | No. 11A, Datun Road, Chaoyang District, Beijing 100101, China |
| Data sharing policy | ***Data*** from the Global Change Research Data Publishing & Repository includes metadata, datasets (in the *Digital Journal of Global Change Data Repository*), and publications (in the *Journal of Global Change Data* & *Discovery*). ***Data*** sharing policy includes: (1) ***Data*** are openly available and can be free downloaded via the Internet; (2) End users are encouraged to use ***Data*** subject to citation; (3) Users, who are by definition also value-added service providers, are welcome to redistribute ***Data*** subject to written permission from the GCdataPR Editorial Office and the issuance of a ***Data*** redistribution license; and (4) If ***Data*** are used to compile new datasets, the 'ten per cent principal' should be followed such that ***Data*** records utilized should not surpass 10% of the new dataset contents, while sources should be clearly noted in suitable places in the new dataset[12] |
| Communication and searchable system | DOI, CSTR, Crossref, DCI, CSCD, CNKI, SciEngine, WDS/ISC, GEOSS |

variable information to achieve a rapid solution for variable selection. The Lasso regression method is widely used in the reconstruction and prediction of climate variables. In this study, the statistical relationship between sea ice albedo and sea level pressure (SLP) is modelled at each grid cell based on remotely observed sea ice albedo data and sea level pressure reanalysis data. The model is driven by global SLP data from the CMIP6 past 1000 experiment and the CMIP5 historical experiment to reconstruct the changes in Arctic summer sea ice albedo between 850–2005 A.D. Since the albedo of sea ice and seawater differ significantly, the conversion threshold between ice albedo and extent is determined by comparing the reconstructed albedo with the remotely observed sea ice areal extent. Finally, the Arctic sea ice areal changes between 850–2005 A.D. are extracted accordingly.

### 3.2 Data Processing

This dataset is based on the newly released CLARA-A2-SAL black sky surface albedo record acquired by the Advanced Very High Resolution Radiometer Sensor (AVHRR) deployed aboard NOAA satellites. These satellites observed sea ice albedo for the Climate Monitoring Satellite Application Facility (hereafter referred to as CMSAF) project in order to establish a relationship between surface albedo and the Large Scale Circulation Index-SLP; the goal of which is to reconstruct summer sea ice areal extent in the Arctic over the past millennium. The algorithm consists of four main steps (Figure 1). First, in order to develop a reliable estimate of the regression coefficients, the independent variable factor in the regression equation is increased according to the monthly data immediately preceding and following the month being reconstructed; specifically, if August data are used as the

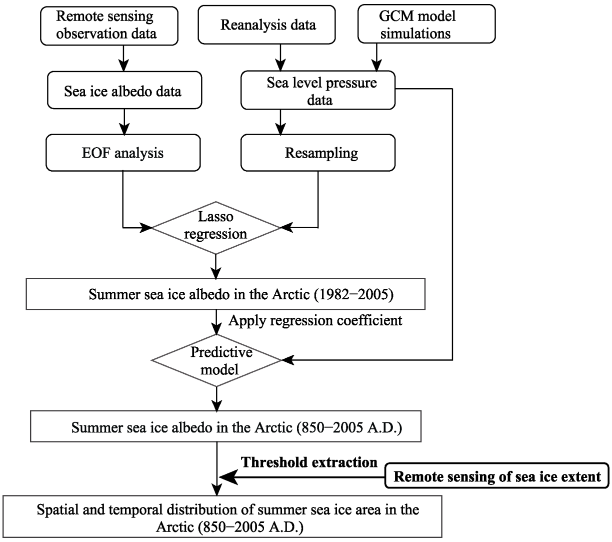


**Figure 1** Technical route of the dataset development

independent variable factor in the regression equation, then July and September data will also be used as the independent variable factor when using the regression model (similar method for June and September data). Secondly, based on Empirical Orthogonal Function decomposition analysis (EOF), the first 30 principal components (PC) of the albedo data for the selected months in CMSAF were extracted for the Arctic region from 1982–2015, and the SLP data were resampled to 10°×10°. Then, the SLP data was used as the independent variable to build an empirical statistical model, using the Lasso regression method, between the albedo PC information and the SLP monthly normalized time series. The operations were performed iteratively to find the optimal regression coefficients. Based on this, the global SLP data from the Earth's climate system model are input into the prediction model to reconstruct the summer sea ice albedo in the Arctic from 850–2005 A.D. Finally, the conversion threshold between albedo and sea ice extent is determined by comparing the reconstructed albedo results with the remotely observed sea ice extent, and the temporal fluctuation of Arctic sea ice area over the past 1,000 years is extracted accordingly.

## 4 Data Results and Validation

The data were compressed in a data file (ArcticSeaIceArea850-2005.rar), and the decompressed data were placed in a data statistics table and four data folders (Table 2).

**Table 2** Composition of data files for the Reconstructed dataset of Arctic summer sea ice area (850–2005)

| Data files and folders | Data file name | Data size (KB) |
|---|---|---|
| ArcticSeaIceArea850-2005.rar | | 684.85 |
| 1_Arctic_Sea_Ice_Area_850-2005.xlsx | | 54,864 |
| 2_ValidationData | | |
| SeaIceAlbedo1982-2005_Observed&Reconstructed | Observed.txt | 1,210 |
| | Reconstructed.txt | 1,225 |
| SeaIceArea1982-2005_Observed&Reconstructed | Observed&Reconstructed.txt | 784 |
| SpatialSeaIce1259,2003_Reconstructed | 1259.nc | 32,308 |
| | 2003.nc | 32,308 |
| SpatialSeaIceAlbedo2005_Observed&Reconstructed | Observed.nc | 473,440 |
| | Reconstructed.nc | 473,440 |

The reconstructed 850–2005 Arctic summer sea ice areal fluctuations ranged from a maximum of 8.7 million km$^2$ in 1259 to a minimum of 5.39 million km$^2$ in 2003. The average sea ice area is 7.55 million km$^2$ (Figure 2).

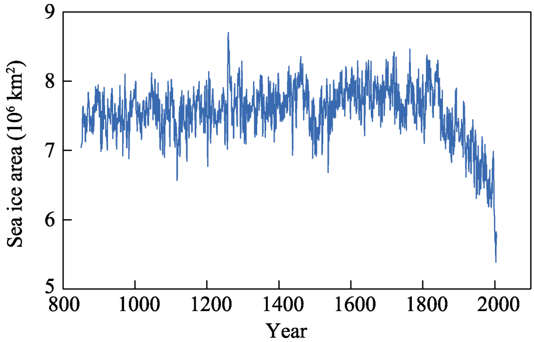


**Figure 2** Summer sea ice area in the Arctic region during 850–2005

The reconstructed Arctic summer sea ice albedo series compared with the remote sensing observation series data is shown in Figure 3. As seen in Figure 3, the reconstructed changes in Arctic sea ice albedo based on the Lasso method are consistent with remote sensing observations. This indicates that the model can sufficiently simulate the rapid decreasing trend in sea ice albedo, driven by the past 30 years of sea ice melt, while also capturing the interannual fluctuations in albedo changes. In terms of spatial correlations, for example, the reconstructed sea ice albedo in the summer of 2005 reflected contemporary observations of the high albedo in the ice covered regions and the low albedo in the nearby ice-free sea (Figure 4).

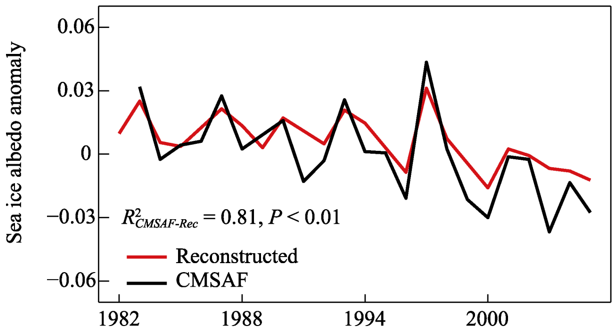


**Figure 3** Comparison of the reconstructed summer sea ice albedo in the Arctic with remote sensing observations (CMSAF)

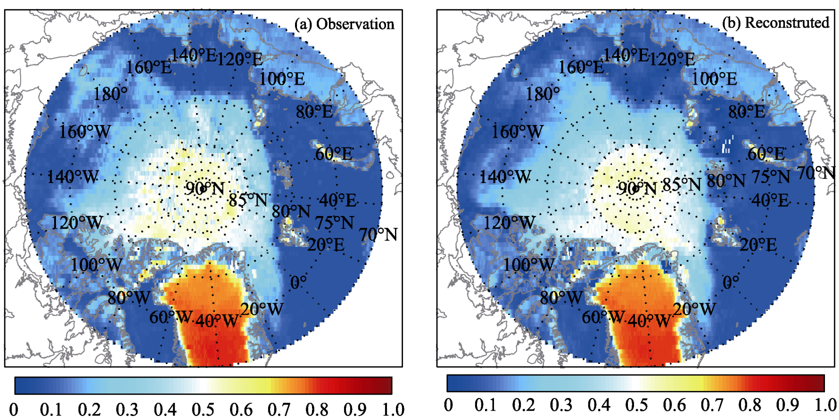


**Figure 4** Spatial distribution of summer sea ice albedo in the Arctic in 2005 from remote sensing observations (a) and reconstructed (b)

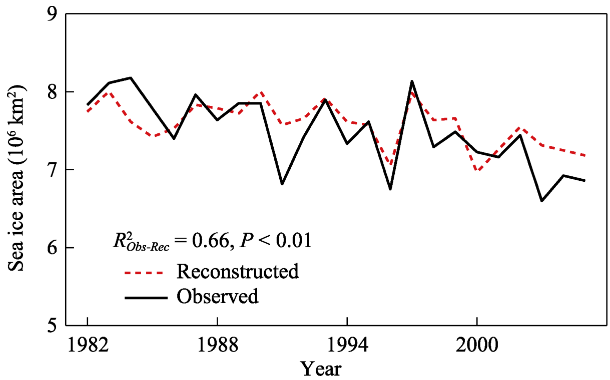


**Figure 5** Comparison of the reconstructed summer sea ice area in the Arctic with remote sensing observations

Since the albedo characteristics of sea ice and seawater differ greatly, the albedo threshold of sea ice-seawater variation can be determined by comparing the reconstructed data with remotely sensed observations. With this threshold, the reconstructed past 30 years of albedo variability can be converted into a record of variable sea ice area, and thus, the spatial and temporal changes in sea ice area over the past 30 years can be extracted. As shown in Figure 4, the sea ice coverage in the Arctic region developed using the Lasso method is consistent with the most recent thirty years of remote sensing observations. As shown in Figure 4, Arctic sea ice areal extent reconstructed based on the Lasso method is consistent with the remotely sensed observations over the last 30 years. The reconstruction better reflects the continuous decreasing trend of sea ice area since 1980 and captures the minimum and maximum values of sea ice areal extent in the summers of 1996 and 1997. The above results indicate that this method can be used for the reconstruction of sea ice areal extent at longer scales over the historical period.

Using the reconstruction algorithm proposed in this study, a millennial-scale time-series of Arctic sea ice areal variability was reconstructed for the period between 850 A.D. and 2005 A.D. This was accomplished by combining simulated SLP data extracted from the CMIP6 past1000 experiment with historical simulations provided by the CMIP5 multimodel comparison program. The results show changes in sea ice areal variability over the past millennium (850–2005 A.D.), and that the long-term decreasing trend of sea ice coverage is correlated with changing Arctic temperatures (Figure 6). During the Medieval Warm Period (800–1300 A.D.), Arctic sea ice area slowly expanded as temperatures in the Arctic gradually decreased. This is consistent with the proxy-based reconstruction of past sea ice coverage developed by Kinnard *et al.* (2011)[13]. The rapid increase in Arctic temperatures since the 19th century is one of the principal drivers of modern sea ice retreat. These results also show that the area covered by Arctic sea ice has rapidly declined over the past two centuries. This is especially true over the last 30 years, during which time the rate of sea ice area reduction exceeded the rate of change observed over the past millennium. This is also consistent with the conclusions of the proxy-based reconstructions[13]. These changes can also be observed spatially. Figure 7 shows a retreat of Arctic summer ice poleward of 75° N in 2003 that is not observed in 1259.

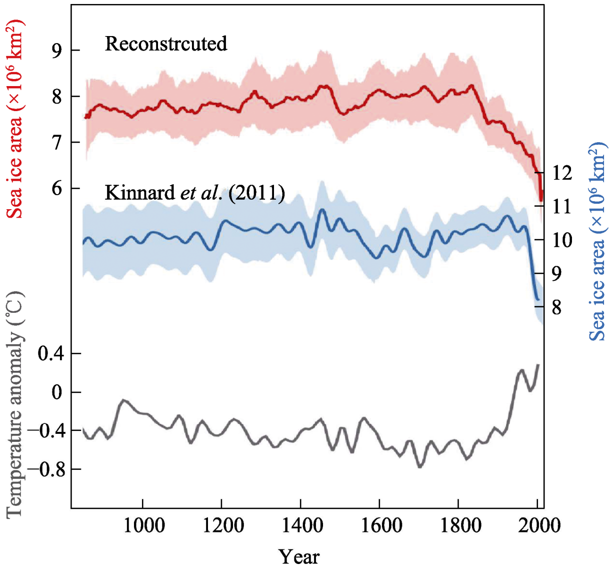


**Figure 6** Reconstructed millennial-scale sea ice area series (red), sea ice series reconstructed by proxy indicators (blue), and Arctic near-surface temperature series (grey)[14]

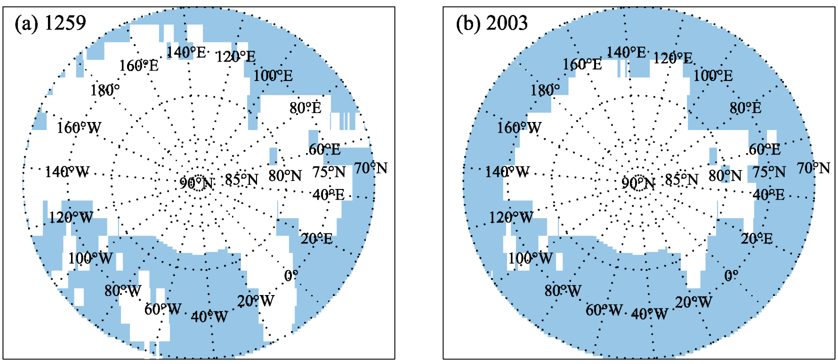


**Figure 7** Reconstructed Arctic summer sea ice distribution for 1259 and 2003 (the reconstructed sea ice in white)

## 5 Discussion and Conclusion

The sea ice-atmosphere statistical model constructed using the Lasso method can sufficiently simulate melt-driven changes to the Arctic albedo. The reconstructed sea ice coverage variability based on this method is in good agreement with the most recent 30 years of remote sensing observations. While the model can simulate both the recent observed trend of rapid sea ice ablation and variability in its spatial extent, the model can also reflect the interannual fluctuations of ice coverage. For example, the model depicted the very low values of sea ice areal extent observed in 2007 and 2012. The reconstructed areal changes in sea ice between 850 A.D. and 2005 show some variability but are consistent with the areal trends reconstructed by Kinnard *et al.*[13] using proxy indicators. The modelled results show that the area covered by Arctic sea ice has declined rapidly over the last two centuries. This decline is most evident within the last 30 years, during which time the rate of ice reduction surpassed the ranges of sea ice variability observed at any other point in the preceding millennium. The recent sea ice areal reduction indicates that climate change driven by rising atmospheric greenhouse gas concentrations plays a crucial role in influencing sea ice area. It is worth noting that although temperature in the historical period is the main factor influencing the long-term trend of sea ice areal change, the sea ice area time series does not correspond exactly to the temperature records for the Arctic. For example, during the Little Ice Age (1450–1850 A.D.), the temperature in the Arctic region showed a decreasing trend, but the reconstructed sea ice data did not reveal a significant increasing areal extent and instead showed variable change. Overall, this millennial-scale sea ice reconstruction reflects an increase in sea ice coverage during decreasing temperature in the Middle Ages and also depicts the rapid decreasing trend of sea ice observed in recent decades. Future work will investigate the uncertainty of this reconstruction method to improve the accuracy of these results.

### *Author Contributions*

Guo, H. wrote the paper, constructed the statistical model of sea ice albedo-atmospheric circulation and is responsible for the simulation of historical sea ice change; Ren, S. participated in writing the paper and producing the dataset.

### *Conflicts of Interest*

The authors declare no conflicts of interest.

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