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Arctic Sea Ice in the First Half of the 20th Century: Temperature-Based Spatiotemporal Reconstruction

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Abstract—Global warming in the recent decades has been accompanied by a rapid decline of the Arctic sea ice area (SIA) in summer (11% per decade). To understand the reasons for such changes, it is necessary to evaluate the range of long-term variability of the Arctic sea ice in the period before a significant increase of anthropogenic emissions of greenhouse gases into the atmosphere. Current empirical data on the spatiotemporal dynamics of Arctic sea ice until the 1950s have significant gaps. In this study, monthly average gridded sea-ice concentration (SIC) fields in the first half of the 20th century are reconstructed using the relationship between the spatiotemporal patterns of SIC variability and surface air temperature over the Northern Hemisphere. The reconstructed data show a significant negative anomaly of the Arctic SIA (about 1.5 million km^2 in September and 0.7 million km^2 in March) in the mid-20th century, which is considerably larger than the corresponding anomaly in other gridded SIC datasets.

Keywords: Arctic sea ice, mid-20th century warming, Arctic climate

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INTRODUCTION

The decline in Arctic sea-ice area (SIA) in the recent decades seems to be the most spectacular and the most precisely observed manifestation of global current climate changes. Continuous satellite observations since 1978 have made it possible to reconstruct sea ice concentrations (SIC) from passive-microwave measurements [1]. According to these data, the Arctic SIA over the past 40 years of observations has decreased in September, the month of a seasonal Arctic SIA minimum, by 2.57 million km^2, or by 41%. The reduction is much slower in winter, and in March, the month of a seasonal Arctic SIA maximum, it is 0.69 million km^2 (4.8%). Moreover, the SIA in winter decreases primarily in the Barents Sea and in the Sea of Okhotsk, where only over the past 20 years has it reduced by 34% and 14%, respectively [2]. Such changes strongly enhance heat fluxes to the atmosphere and rearrange the regional and large-scale atmospheric circulation, particularly inducing weather anomalies across Russia [2]. The current decrease of Arctic SIA in paleoreconstructions [3] is unprecedented for the past 1000 years.

Before the era of routine satellite observations, the Arctic SIA was monitored using coastal, ship, or aircraft observations and drifting buoys. Such observations allowed the creation of the gridded Arctic SIC data set starting from 1953 [4]. These data have been further augmented by satellite data to form a basis of all up-to-date gridded SIC data sets used for climate-change analysis (including the reports of the Intergovernmental Panel on Climate Change), for comparison with climate model results, and as boundary conditions in atmospheric reanalyses and atmospheric general circulation models (AGCMs) (Met Office Hadley Center Sea Ice and Sea Surface Temperature (HadISST) data set in different versions [6]).

Prior to 1953, information on SICs in the Arctic is limited (in space, season, or length of record), heterogeneous (differing in observation and analysis methods), and cannot provide a clear picture of changes in the total area of the Arctic sea ice or regional sea ice variations. Because of this, changes in the Arctic SIA in the gridded data sets from the early 20th century to the 1950s show the relatively small amplitude and no significant long-term fluctuations comparable to the present one. In some periods, for example, during World War II, the data have been simply replaced by a climatology [6]. Such dynamics of the Arctic SIA in the first half of the 20th century is inconsistent with a strong Arctic warming in that period, comparable by its pace to the present day warming [7]. Regional data in the Russian Arctic seas show a significant decrease in summer sea ice in the mid-20th century [8]. Considerable long-term quasi-periodic SIA fluctuations are evident in the regional indices of Atlantic Arctic sea ice and in paleoproxy reconstructions for the last

400 years, which suggests that these fluctuations are linked to the Atlantic Multidecadal Oscillation (AMO) [9]. However, the positive phase of the AMO in the mid-20th century according to [6] was accompanied by a decrease in the Arctic SIA in neither winter nor in summer. Numerical experiments with AGCM using the data [6] as boundary conditions have shown that, given no significant (about 1 million km^2) negative SIA anomaly in the mid-20th century, the model fails to reproduce winter Arctic surface temperature anomalies, yet it almost perfectly reproduces temperature changes since the second half of the 20th century [10].

TEMPERATURE-BASED RECONSTRUCTION OF ARCTIC SIA

The relationship between surface air temperature (SAT) and SIC [2] and availability of long-term records of station temperature observations in the Arctic zone allow one to use SAT for Arctic SIA reconstructions when there is no sufficient amount of in situ observations. Station data, because of a significant radius of spatial correlation of temperature anomalies, permit the creation of gridded Northern Hemisphere data sets of land temperature anomalies spanning the entire 20th century, which can be used for reconstructions [11]. Such an approach has recently been applied to reconstruct changes in the seasonal and annual mean SIA for the entire Arctic or for its sectors [12, 13]. Estimates of the negative Arctic SIA anomaly in the mid-20th century in such reconstructions are much greater in amplitude than those in [6].

However, such estimates do not give any information on the spatial pattern of SIC changes, thereby preventing them from being used as boundary conditions for AGCMs or for regional studies. Importantly, the linear relationship between the two relatively short (less than 40 years) data time series with a strong climatic trend in the presence of significant multidecadal variations (typically 60 to 70 years in period) and interannual variability, presumably of different origin (greenhouse effect, AMO, and natural atmospheric and oceanic circulation variations) and, hence, with a different spatial pattern, may lead to incorrect estimates of the long-term Arctic SIA fluctuations in the period of reconstruction. Additionally, the link between the SIC in the Arctic seas and the SAT can be remote, with maximum correlations over land areas at midlatitudes and even in the subtropics [2].

Another gridded monthly mean SIC data set, referred to as Sea Ice Back To 1850 (SIBT1850), filling gaps before the satellite era by synthesizing regional data and using analog based estimations, has recently been published [14]. The SIBT1850 data show a significant negative Arctic SIA anomaly in the mid-20th century. It should be noted that, probably due to the heterogeneity of the data and methods used for the synthesis, SIBT1850 has not yet been widely used in research.

An alternative way of using the SAT–SIC relationship in the reconstruction of the past Arctic SIA is the decomposition of spatiotemporal SIC and SAT datasets in empirical orthogonal functions (EOFs). The first EOF represents a spatial pattern explaining the maximum time variability of the original data set. The second EOF describes the maximum variability of the residual after subtracting the variability related to the first EOF, to the fulfillment of the orthogonality condition, etc. In such a formulation of the problem, EOFs are the eigenfunctions of the covariance matrix of the data set [15].

The first four EOFs of SIC anomalies for all months of 1953–2016 account for 80% of variability or more, while six leading EOFs of Northern Hemisphere land SAT anomalies (from [11]) north of 30° N for 1900–2016 explain roughly 90% of temperature variability. This makes it possible, for the reliable HadISST1 SIC data period (1953–2016), to construct a regression model for SIC EOF principal component series using the SAT EOF principal components as independent variables. The procedure of SIC reconstruction for 1900–1952 is as follows.

Monthly mean SIC fields SIC(φ, λ, t) for each month in the 1953–2016 period of fairly reliable data are approximated by a sum of the four spatial $\mathrm{EOF}_i^{\mathrm{SIC}}(\varphi,\lambda)$ with principal components $PC_i^{\mathrm{SIC}}(t)$

$$\mathrm{SIC}(\varphi,\lambda,t)=\sum_{i=1}^{N=4}PC_i^{\mathrm{SIC}}(t)\,\mathrm{EOF}_i^{\mathrm{SIC}}(\varphi,\lambda),$$

where φ, λ, and t are the latitude, longitude, and time indices, respectively. The surface-air temperature anomaly fields $TS(\varphi, \lambda, t)$ for 1900–2016 are also approximated by a sum of EOFs as

$$TS(\varphi,\lambda,t)=\sum_{j=1}^{N=6}PC_j^{TS}(t)\,\mathrm{EOF}_j^{TS}(\varphi,\lambda).$$

For 1953–2016, the least-squares method is used to calculate coefficients b_j^i of the multiple linear regression of $PC_i^{\mathrm{SIC}}(t)$ onto $PC_j^{TS}(t)$, from which principal components for the reconstructed ice concentration $PC_{re}^{\mathrm{SIC}}(t)$ and SIC field $\mathrm{SIC}_{re}(\varphi,\lambda,t)$ over 1900–1952 can be retrieved as

$$PC_{re}^{\mathrm{SIC}}(t)=\sum_{j=1}^{N=6}PC_j^{TS}b_j^i,$$

$$\mathrm{SIC}_{re}(\varphi,\lambda,t)=\sum_{i=1}^{N=4}PC_{\mathrm{re}}^{\mathrm{SIC}}(t)\mathrm{EOF}_i^{\mathrm{SIC}}(\varphi,\lambda).$$

This model is able to reconstruct SIC EOF principal components for 1900–1952 and, consequently, SIC fields for that period. Such a procedure was carried out for all 12 months. If the reconstructed SIC values were negative or above 100%, they were assigned 0% and 100%, respectively. Note that such

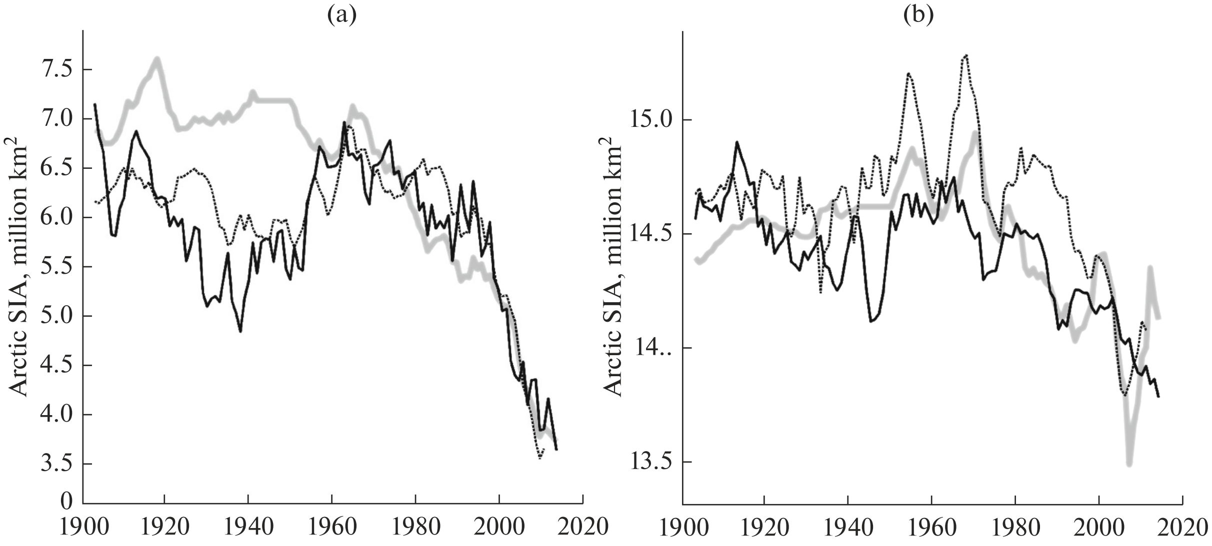

Fig. 1. SIA (mln km^2) (smoothed with a 5-year running mean) for (a) September and (b) March from HadISST 1.1 (thick grey line), SIBT1850 (Walsh) (black dotted line), and reconstruction based on linear regression of SIC onto SAT (black line).

values were few and, as a rule, represented no more than 2 to 3% of the data array. The use of only the first four and six EOFs for SIC and SAT, respectively, was due to a very modest improvement in the results when more EOFs were used. A similar procedure was applied to reconstruct the total Arctic SIA from proxy records for the past 1000 years [3].

RESULTS

The total area of the Arctic sea ice in March and September from the reconstructed data is shown in Fig. 1 in comparison with HadISST1 and SIBT1850 data. For September (Fig. 1a), the month of the largest Arctic SIA reduction during the present period, the three data sets all show closely consistent changes since the early 1960s with an Arctic SIA decrease of approximately 3 million km^2, an indication of the skill of our reconstruction technique. Whereas the HadISST1 data generally demonstrate no climatic trends with some decadal fluctuations in the period 1900–1960, SIBT1850 shows a persistent negative Arctic SIA anomaly during the mid-20th century warming with a long-lasting minimum in the 1930s to the 1940s. The anomaly is about 0.7 million km^2 relative to the SIA in the beginning of the 20th century. In the reconstructed data, this anomaly is approximately twice as large, about 1.5 million km^2, with a minimum in the late 1930s.

For March (Fig. 1b), significant discrepancies in Arctic SIA between different data sets are also evident during the present period. It should be noted that the reconstructed data describe the Arctic SIA dynamics from the “reference” (for that period) HadISST1 data better than SIBT1850. In particular, while the Arctic SIA in SIBT1850 systematically exceeds HadISST1 from the late 1970s to the latter half of the 1990s, its value in the reconstructed data is closely consistent with HadISST1. Two noticeable Arctic SIA maxima in HadISST1 in the mid-1950s and in SIBT1850 in the late 1970s are approximately twice as large in amplitude and are entirely missing in the reconstructed data. Note that such decadal Arctic SIA fluctuations in SIBT1850 and HadISST1 disagree with the anomalies of winter Arctic temperature [10], which raises the question of whether these anomalies are realistic. The negative Arctic SIA anomaly in the mid-20th century, missing in HadISST1, is apparent in both SIBT1850 and reconstructed data. The amplitude of the negative anomaly is larger in the reconstructed data than in SIBT1850, with a magnitude of approximately 0.4 and 0.6 million km^2, respectively. A minimum in the reconstructed data occurs later and occurs in the mid-1940s, coinciding in time with a winter SAT maximum in the Arctic. It should be noted that decadal Arctic SIA fluctuations in the reconstructed data and in SIBT1850 are anticorrelated.

The spatial SIC changes during the mid-20th century warming (1935–1945) relative to the early 20th century period (1905–1915) for March and September derived from the different data sets are shown in Fig. 2 in comparison with HadISST1 dataset during the present-day warming period (Figs. 2d, 2h). There are no significant SIC changes in the mid-20th century in HadISST1 (Figs. 2c, 2g), relatively small anomalies in SIBT1850 (Figs. 2b, 2f), and an essential SIC decrease in the reconstructed data mainly in the Greenland and Barents seas (Figs. 2a, 2d). The spatial anomaly pattern is similar to the recent changes, but shows a much larger SIC decrease in the Greenland Sea. In September, the spatial pattern of the SIC

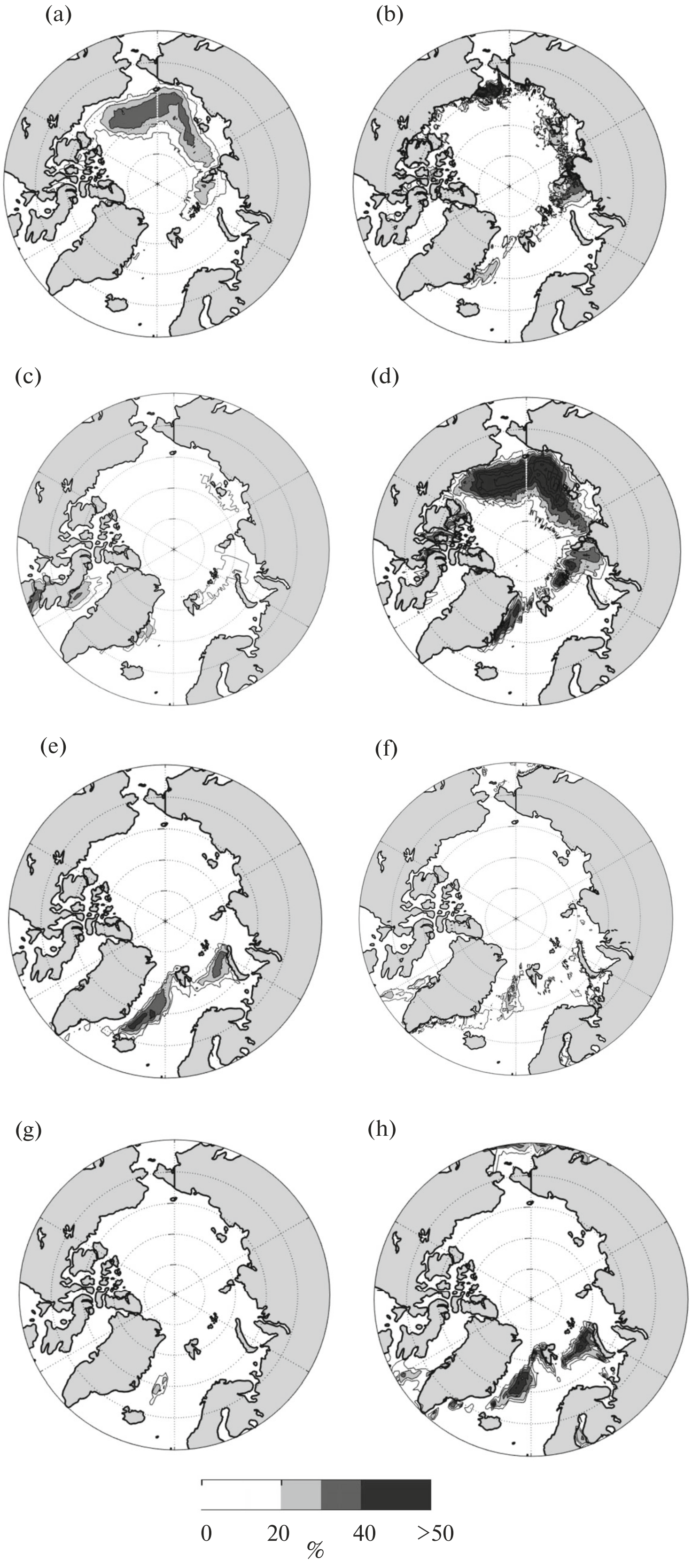

Fig. 2. Differences in SIC (%) for (a, b, c, d) September and (e, f, g, h) March between averages over 1905–1915 and 1935–1945 from (a, e) reconstructed data, (b, f) SIBT1850, and (c, g) HadISST 1.1. (d, h) Differences between 1970–1980 and 2000–2010 from HadISST 1.1.

anomalies in the reconstructed data is similar to the current changes, with a maximum reduction decline in the sector 120° E– 120° W, but has larger amplitude and has no significant anomalies in the Greenland Sea (Fig. 2a).

CONCLUSIONS

The spatiotemporal reconstruction of SIC in the Arctic over the period 1900–1952 shows a significant negative Arctic SIA anomaly in the mid-20th century, which is missing in HadISST1 dataset. The amplitude of the anomaly is roughly 1.5 million km^2, or twice as large as the anomaly in SIB1850, and has a different spatial pattern. Our estimates are overall consistent with the reconstruction of the total Arctic SIA in September in [12]. The Arctic SIA reduction in the mid-20th century from our reconstructed data remained record breaking through the 20th century until the early 2000s, when the melting of Arctic sea ice has accelerated (Fig. 1). The reconstructed wintertime changes also show a larger Arctic SIA reduction than that in the other data sets. The negative Arctic SIA anomaly in the mid-20th century is consistent with a simultaneous warming in the Arctic in that period, and they can both be a consequence of the long-term natural climatic variability, thereby indicating a possible significant contribution of such variability to the current SIA and temperature changes in the Arctic.

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