

Relationship of the Extent of Antarctic and Arctic Ice with Temperature Changes, 1979–2020

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Abstract—Quantitative estimates of the relationship between interannual variations in the extent of Antarctic and Arctic sea ice and changes in the surface air temperature in the Northern and Southern hemispheres are obtained using satellite, ground-based, and reanalysis data for the past four decades (1980–2019). It is shown that the previously noted general increase in the extent of Antarctic sea ice observed until recent years from satellite data (available only since the late 1970s) over the background global warming and a rapid decrease in the extent of Arctic sea ice is associated with a regional decrease in the surface temperature at Antarctic latitudes from the end of the 1970s. This is a result of regional manifestation of natural climate variations with periods of up to several decades against the background of global secular warming with a relatively weak temperature trend over the ocean in the Southern Hemisphere. Since 2016, a sharp decrease in the extent of Antarctic sea ice in the Southern Ocean has been observed. The results of the correlation and cross-wavelet analysis indicate significant coherence and negative correlation with the surface temperature of the extent of sea ice in recent decades, not only in the Arctic, but also in the Antarctic.

Keywords: Antarctic, Arctic, extent of sea ice, surface temperature, satellite and ground-based monitoring, reanalysis data, anomalies and trends, natural and anthropogenic factors

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INTRODUCTION

In recent decades significant climate changes have been observed, which are most pronounced at high latitudes [1–3]. In the first two decades of the 21st century, the rate of decrease in the extent of sea ice in the Arctic was so fast that, until recently, only a few climate models in the world were able to reproduce adequately the changes noted from satellite data since the late 1970s [1, 4]. Many studies have been devoted to study of this problem among many other modern climate problems (see, for example, [1, 5–11]). This paper analyzes the features of the relationship of the interannual variability of the Antarctic and Arctic sea ice with the changes in the surface temperature in the Arctic and Antarctic as well as in the Northern (NH) and Southern (SH) hemispheres as a whole, based on the data collected in recent decades.

DATA AND METHODS

The monthly average satellite NSIDC data (<http://nsidc.org>) were used for the analysis of the

extent (area) and concentration of sea ice in the Arctic and Antarctic in recent decades from January 1979 to June 2020 [15]. Satellite NSIDC data include both the area of sea ice and its total extent, which is greater; this is due, in particular, to the problem of detecting the ice cover using satellite measurements in open water leads.

To assess the relationship between sea ice and temperature variations, we used the corresponding monthly average data of the ERA5 reanalysis (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>) for the surface temperature (see [13]), and also the GISS data (<https://data.giss.nasa.gov/gistemp/>) based on observations [14].

Linear regressions and estimates of the statistical significance were used to evaluate the parameters of the sensitivity of the total area and total extent of sea ice to the changes in the surface temperature. The peculiarities of the sea ice variability and temperature regime were studied with the use of wavelet analysis. We used cross-wavelet analysis along with correlation analysis to assess the relationship between sea ice regimes at polar latitudes and variations in the temperature regime.

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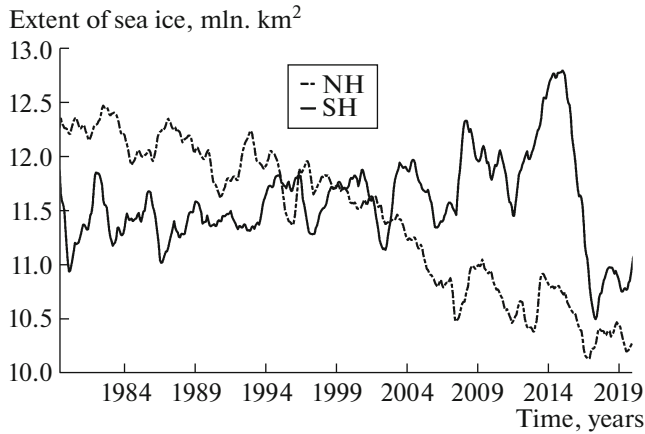


Fig. 1. Changes in the extent of sea ice in the Arctic (dashed line) and Antarctica (solid line) based on monthly average satellite data from January 1979 to June 2020 with running annual averaging.

RESULTS OF ANALYSIS

A sharp decrease in the ice cover in the Southern Ocean has been observed against the background of a rapid decrease in the total extent of the Arctic sea ice caused by strong Arctic warming in recent decades and a general increase in the extent of sea ice in Antarctica since 2016 (Fig. 1). Changes in the extent of the Antarctic and Arctic sea ice in recent decades are naturally associated with the changes in the temperature regime.

The overall increase in the extent of sea ice in Antarctica observed up to 2016 is due to the fact that satellite data of the extent of sea ice have only been avail-

Table 1. Quantitative estimates of the sensitivity of the total extent of the Arctic and Antarctic sea ice *S* based on the satellite data to changes in the surface temperature *T* in the Arctic and Antarctic based on the ERA5 reanalysis data in different months of interannual variability, 1980–2019

Months	<i>dS/dT</i> , mln. km ² /K 1980–2019	
	Arctic	Antarctica
January	-0.28(±0.05) [-0.69]	-0.54(±0.27) [-0.28]
February	-0.25(±0.06) [-0.58]	-0.19(±0.14) [-0.21]
March	-0.28(±0.06) [-0.61]	-0.69(±0.12) [-0.68]
April	-0.31(±0.05) [-0.71]	-0.57(±0.12) [-0.63]
May	-0.47(±0.08) [-0.68]	-0.34(±0.10) [-0.49]
June	-0.90(±0.09) [-0.83]	-0.34(±0.11) [-0.44]
July	-1.58(±0.22) [-0.76]	-0.23(±0.06) [-0.52]
August	-1.63(±0.17) [-0.84]	-0.03(±0.08) [-0.06]
September	-1.17(±0.11) [-0.87]	0.08(±0.10) [0.14]
October	-0.77(±0.05) [-0.93]	-0.08(±0.12) [-0.10]
November	-0.41(±0.04) [-0.84]	-0.45(±0.14) [-0.47]
December	-0.37(±0.05) [-0.79]	-0.80(±0.24) [-0.48]

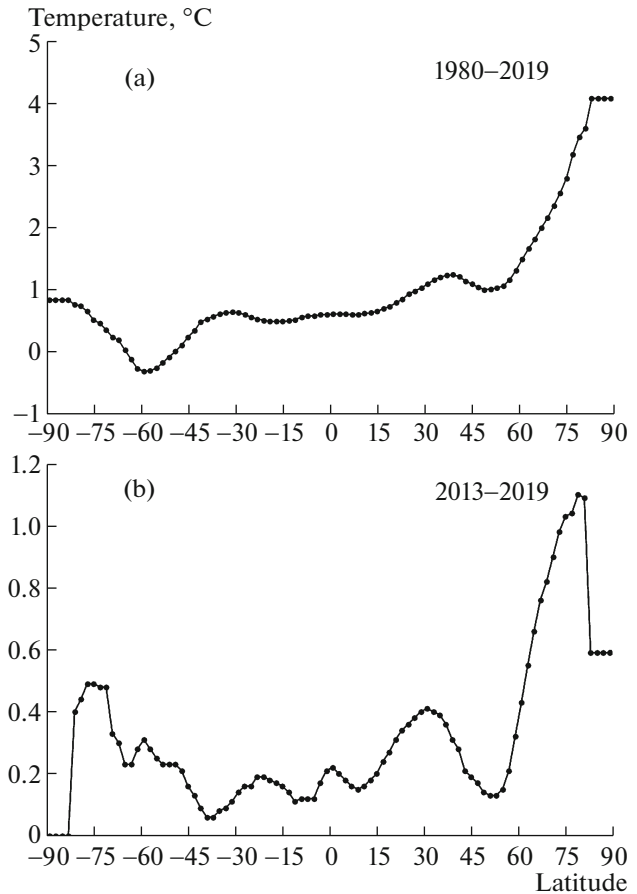


Fig. 2. Variations in the average annual surface temperature in (a) 1980–2019 and (b) 2013–2019 based on the GISS data at different latitudes.

able since the late 1970s. It was a period of a general decrease (although relatively weak) in the ocean temperature of Antarctic waters (Fig. 2). It is seen in Fig. 2a that in the past four decades a general decrease in surface temperature was observed at oceanic Subantarctic latitudes against the background of strong warming at Arctic latitudes (the so-called Arctic amplification). At the same time, in recent years, an increase was observed in surface temperature in all latitudinal zones including Subantarctic oceanic latitudes (Fig. 2b).

The observed regional decrease in the ocean surface temperature in the past four decades against the background of the general warming in the SH can be explained by the significant influence of natural climatic quasi-cyclic processes such as El Niño, Antarctic Oscillation, and Interdecadal Pacific Oscillation. A general increase in the surface temperature of the ocean at Subantarctic and Antarctic latitudes has been already manifested over longer periods, in particular in the last six decades (from the end of the 1950s). A more significant manifestation of the general trend of decrease in the extent of Antarctic sea ice should be

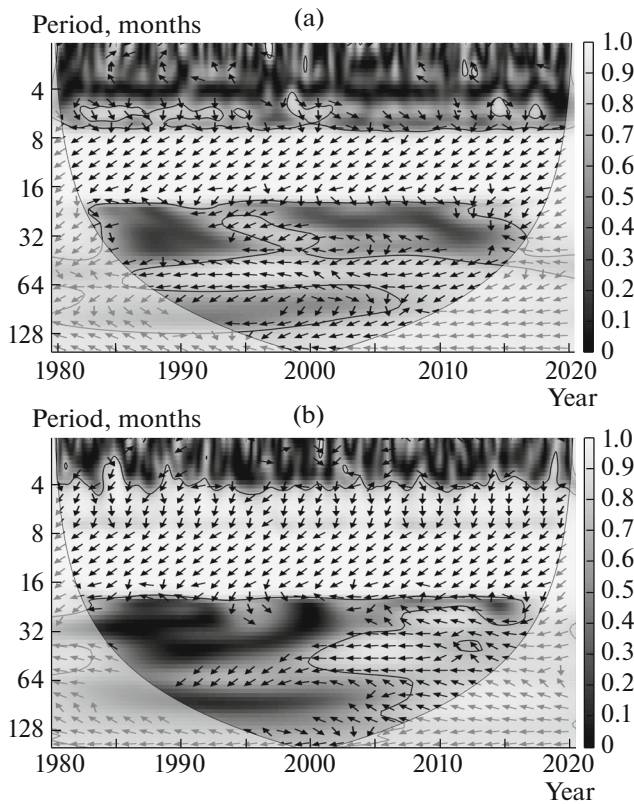


Fig. 3. Local coherence of the extents of (a) Arctic and (b) Antarctic sea ice based on monthly average satellite data with variations in the surface temperature based on monthly average reanalysis data from January 1980 to June 2020. Regions of significant coherence (at the level of 95%) are highlighted; the arrows show the phase shift (arrow to the right denotes in-phase, to the left, anti-phase); regions of boundary effects are also indicated.

expected against the background of general warming as the series of satellite observations on sea ice continue to increase in the future. Clear signs of this have appeared since 2016 [10, 13]. It should also be noted that there are significant differences in the processes of heating and cooling of the ocean with the changing extent (area) of sea ice in the annual cycle in the NH and SH including the Arctic and Antarctic latitudes [14].

Table 1 presents quantitative estimates of the sensitivity of the total extent of the Arctic and Antarctic sea ice (S in mln. km² based on satellite data) to the changes in the surface temperature (T in K degrees) in the Arctic and Antarctic based on the ERA5 reanalysis data in different months of the interannual variability in 1980–2019. The sensitivity parameters estimated from the coefficients of the corresponding linear regressions, which are significant at a level of two standard deviations and the corresponding correlation coefficients, are obtained. In the Arctic region, the estimates are statistically significant in all months. In Antarctica, a negative correlation between the total

extent of sea ice and the surface temperature was obtained in all months except September; a statistically insignificant positive correlation was noted in this month. Moreover, significant estimates were obtained (at a level of two standard deviations) in most (eight) months of the year. The highest absolute values of the sensitivity parameters dS/dT of the Arctic sea ice were estimated in the summer months (up to -1.6 mln. km² at 1 K warming in the Arctic). The smallest values (absolute values) of the sensitivity parameters dS/dT of the Arctic sea ice were estimated at the end of winter (about -0.3 mln. km² at 1 K warming in the Arctic). The highest values (absolute values) of the sensitivity parameters dS/dT of the Antarctic sea ice were estimated in the summer and autumn months (up to -0.8 mln. km² at 1 K warming in Antarctica).

The corresponding estimates of the sensitivity of the extent of sea ice to the changes in the hemispheric surface temperature were also obtained. It was found that a negative correlation of the total extent of the Arctic sea ice with the surface temperature in the Northern Hemisphere in most months is manifested more greatly for the entire surface temperature of the hemisphere as a whole rather than for solely the surface temperature only in the Arctic. At the same time, the negative correlation of the total extent of the Antarctic sea ice with the surface temperature of the Southern Hemisphere as a whole in most months is less significant than the correlation with the surface temperature only in Antarctica.

The peculiarities of the relationship between the total extent of sea ice and the temperature regime can be estimated in more detail using cross-wavelet analysis. Figure 3 shows the local coherence of the extents of (a) Arctic and (b) Antarctic sea ice (based on the monthly average satellite NSIDC data) with the variations in the surface temperature in the (a) Arctic and (b) Antarctic based on the monthly average data of the ERA5 reanalysis from January 1980 to June 2020. Figure 3a provides evidence about the significant coherence between the variations in the extent of the Arctic sea ice and the corresponding variations in the surface temperature in the Arctic, not only in the annual cycle, but also for longer-term interdecadal variations. Figure 3b shows that, unlike the annual cycle, significant coherence of interdecadal variations in the extent of the Antarctic sea ice with the corresponding variations in the surface temperature in Antarctica has been manifested only in the last decade and a half.

A similar cross-wavelet analysis was carried out for the extent of the Arctic and Antarctic sea ice based on the monthly average NSIDC satellite data with variations in the surface temperature in the NH and SH as a whole based on the monthly average ERA5 reanalysis data from January 1980 to June 2020. It is important that the coherence of long-term variations in the

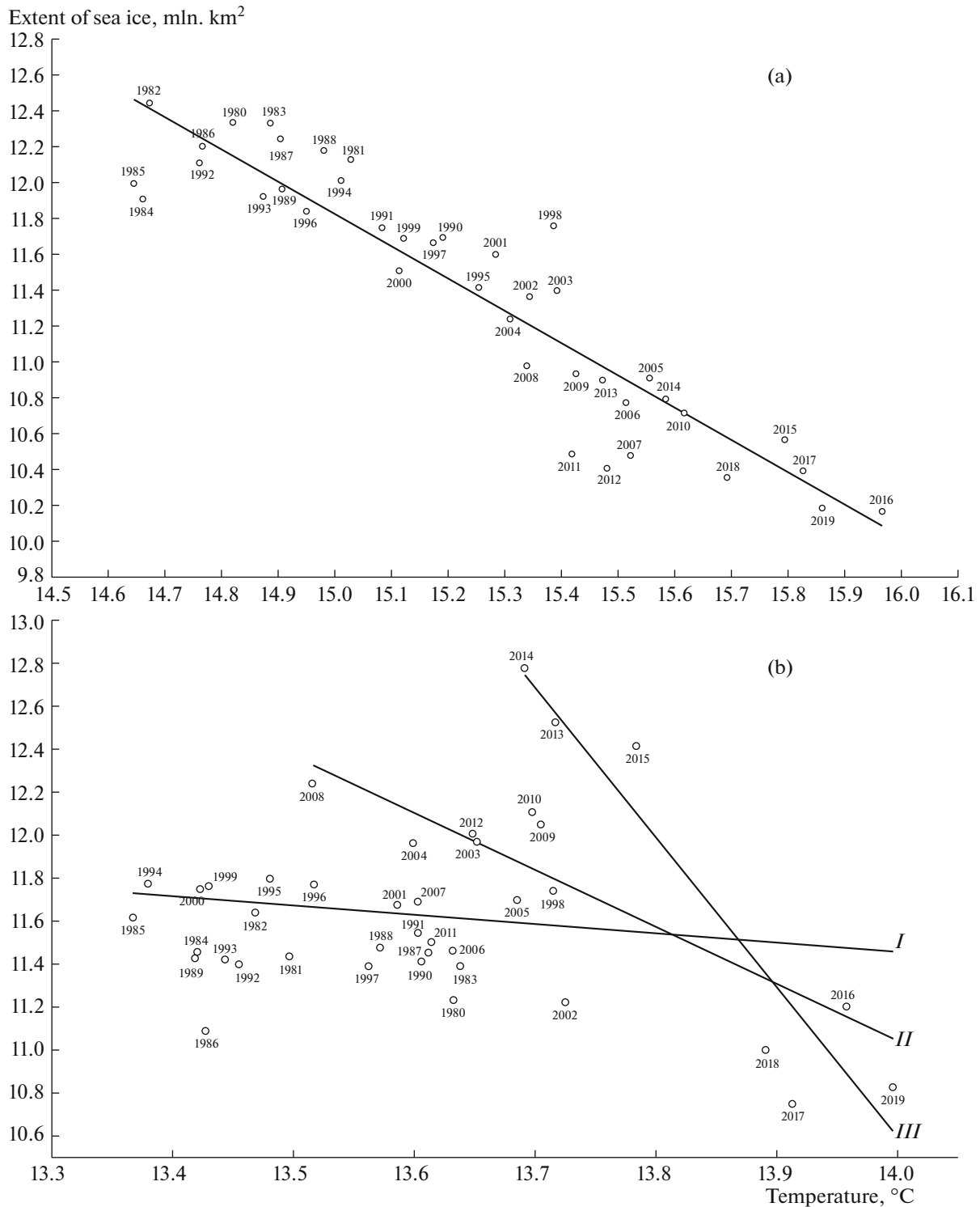


Fig. 4. Average annual extent of sea ice in the (a) Arctic and (b) Antarctic based on satellite NSIDC data in the period 1980–2019 depending on the mean annual surface temperature in the (a) NH and (b) SH based on the ERA5 reanalysis data. Straight lines show the corresponding linear regressions over (I) the entire period for the NH and SH, as well as over two subperiods for the SH (II, 2003–2019; III, 2013–2019).

Antarctic sea ice with the variations in the surface temperature of the NH was significant over the entire period analyzed. At the same time, the coherence of

variations in the extent of the Antarctic sea ice with variations in the surface temperature in the SH has significantly increased in recent years and is manifested

in a wide range: from variations in the annual cycle to interdecadal variations.

Figure 4 shows the dependences of the extent of sea ice in the (a) Arctic and (b) Antarctic on the surface temperature in the (a) NH and (b) SH based on the average annual ERA5 reanalysis data in the period 1980–2019. The relationship between the extent of sea ice S in the Arctic and surface temperature T in the NH in the entire 40-year period under study is characterized by a high correlation coefficient ($r = -0.93$). The linear regression coefficients of S with respect to T (straight lines in Fig. 4) can be used to estimate the corresponding sensitivity parameters dS/dT . The parameter of sensitivity dS/dT of the extent of the Arctic sea ice to the changes in the surface temperature in the NH based on the average annual data over the entire 40-year period is estimated at $1.8 (\pm 0.1)$ mln. sq. km/K (Fig. 4a).

The parameter of sensitivity of the extent of the Antarctic sea ice to the changes in the surface temperature in the SH based on the average annual data over the entire 40-year period is estimated at $-0.4 (\pm 0.4)$ mln. km²/K (Fig. 4b). The obtained estimate is statistically insignificant ($r = -0.16$). This is related to different temperature trends in different regions of the SH (with a decrease in the surface temperature in the Subantarctic latitudinal zone) for the period 1980–2019 against the background of hemispheric warming. The observed regional features of temperature and ice changes are associated with natural quasi-cyclic processes, including El Niño phenomena and the Antarctic Oscillation (Antarctic Circumpolar Mode). Similar estimates were obtained for shorter periods over the past two decades: $dS/dT = -2.7 (\pm 0.9)$ mln. km²/K ($r = -0.62$) for 2003–2019 and $dS/dT = -7.0 (\pm 1.2)$ mln. km²/K ($r = -0.94$) for 2013–2019 (Fig. 4b).

CONCLUSIONS

The results of the analysis indicate the significance of natural climate variations with a time scale of up to several decades (associated with key climate modes, including El Niño events and the Antarctic Oscillation) at Antarctic and Subantarctic latitudes with sea ice. The observed temperature peculiarities with a general decrease in the surface temperature at oceanic Antarctic latitudes in recent decades against the background of hemispheric warming clarify the problem of multidirectional trends in the interannual variations in the extent (area) of sea ice in the Arctic and Antarctic based on the satellite data. Satellite data have been available only since the late 1970s; it was precisely this period when a decrease in temperature appeared at the ocean surface at Antarctic latitudes associated with key climate modes.

It is worth noting that, in general, in recent decades, the overall correlation of the extent of the Antarctic sea ice with the surface temperature at Ant-

arctic latitudes is higher than that with the surface temperature of the SH as a whole. In this case, the correlation of the extent of the Arctic sea ice with the surface temperature of the NH is generally higher than with the surface temperature only at Arctic latitudes. The observed peculiarities reveal the differences in the relative role of the regional and global climatic processes in the formation of sea ice and their changes in the Antarctic and Arctic regions in recent decades.

The results of cross-wavelet analysis indicate that, over the past two decades, an increasingly significant negative correlation of long-term variations in the total extent of the Antarctic sea ice with the temperature regime has been manifested in accordance with the prognostic model estimates. At the same time, the parameter characterizing the sensitivity of the average annual extent of the Antarctic sea ice to the changes in the hemispheric surface temperature in the last two decades is even higher than that with the average annual extent of the Arctic ice (see also [15]). The results of cross-wavelet analysis confirm the significant anticorrelation of interdecadal changes in the extent of the Arctic sea ice with the surface temperature in the Arctic and in the NH as a whole over the past four decades. A significant anticorrelation of interdecadal variations in the extent of the Antarctic sea ice in the past four decades with the surface temperature in the SH as a whole was also noted. At the same time, a significant anticorrelation of interdecadal changes in the extent of the Antarctic sea ice with the surface temperature in Antarctica began to manifest itself only in recent years.

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