Changes of the sea ice and snow cover extent associated with temperature changes in the Northern and Southern Hemispheres in recent decades

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Abstract. Changes in snow cover and sea ice extents associated with temperature changes in the Northern and Southern Hemispheres for the period 1979-2020 are analysed using monthly-mean satellite and reanalysis data. Quantitative estimates of the relationship between the Antarctic and Arctic sea ice and changes in the surface air temperature were obtained. Overall increase of the Antarctic sea ice extent is associated with the regional manifestation of natural multidecadal climate modes with periods of up to several decades (against the background of global warming and a rapid decrease in the extent of sea ice in the Arctic). The results of correlation and cross-wavelet analyses show significant coherence and negative correlation of the surface air temperature in both Arctic and Antarctic with the respective sea ice extent in recent decades. Seasonal and regional features of the snow cover sensitivity to changes in the temperature regime in the Northern Hemisphere for the past four decades are noted. The features of snow cover variability in Eurasia and North America are presented.

1. Introduction
The snow-ice cover plays a crucial role in the formation of regional and global climatic regimes [1]. On time scales from seasons to millions of years, the most noticeable and extensive changes in the Earth's surface properties have been associated with changes in the snow-ice cover extent [2]. A decrease in snow-ice cover area (and a corresponding decrease in surface albedo) under the temperature rise contributes to an increased absorption of solar radiation and thereby to a further temperature growth. This process is associated with the strongest positive climatic feedback, which increases the sensitivity of the temperature regimes to external influences – both natural and anthropogenic ones.

The most rapid climatic changes of recent decades have been observed in Arctic latitudes – clearly manifested in a sharp decrease in the total extent of Arctic sea ice [1,3,4]. At the same time, the total Antarctic sea ice extent has been statistically insignificantly growing since the late 1970s, according to satellite data. By 2014, its average annual area reached a record high of about 13 million km², and since 2016 there has been a sharp decrease with reaching the record low since the end of the 1970s.

Multiple studies have been devoted to understanding the Arctic and Antarctic sea ice extent variability [1,3-28]. The peculiarities of Antarctic sea ice variability are attributed to various causes, such as oceanic processes and atmospheric circulation features in the Southern Hemisphere. In particular, [8] the influence of different climatic variability modes, including El Niño and the Antarctic Oscillation, on the Antarctic sea ice extent has been analyzed. In [12], the features of climatic changes in the Antarctic latitudes are associated with the features of oceanic circulation in the Southern Ocean,
more precisely, in the Antarctic latitudes. The connection between the Antarctic sea ice extent and the interannual Pacific Ocean oscillation is revealed in [13]. In [20], features of the relationship between Antarctic sea ice extent and the position of the Antarctic polar front were noted.

According to satellite data since the late 1970s, the maximum of sea ice extent in the Arctic reached 16 million km$^2$, in the Antarctic – about 20 million km$^2$. Variations in the annual extent of snow cover are substantially greater – in the Northern Hemisphere their range reaches 50 million km$^2$. As for the changes in snow cover, both increases and decreases are manifested at the regional level during the warming. Increased precipitation (including solid precipitation during the cold months) due to atmospheric moisture capacity increase contributes to the growth in snow cover extent with warming. Many studies have been dedicated to estimating the current trends of snow cover changes for various regions [1,2,9-48].

This paper presents the results of analysis of the Arctic and Antarctic sea ice extent changes, as well as Northern Hemisphere snow cover changes (including Eurasia and North America), in relation to the surface air temperature variations for recent decades.

2. Data and methods

Changes in the extent of snow cover and sea ice associated with temperature changes in the Northern and Southern Hemispheres are analyzed by using monthly-mean NSIDC (https://www.ncdc.noaa.gov/) and GSL (https://climate.rutgers.edu/) data, as well as ERA5 reanalysis data (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5) for the period 1979-2020 [49].

3. Results and discussion

Figure 1 (a, b) presents the dependences of the total extent of sea ice $S_i$ in the Arctic (a) and Antarctic (b) (according to satellite data) on the surface air temperature $T_H$ in the Northern (a) and Southern (b) Hemispheres (according to the ERA5 reanalysis data) for the months of the period 1979-2020. Considering strong variations in the surface air temperature and the sea ice extent in annual cycle, the corresponding variations in the interannual variability are noted for each month. Figure 1a shows negative correlation of surface air temperature variations and the sea ice extent $S_i$ in the Arctic for each month more clearly.

![Figure 1](image)

**Figure 1.** The extent of sea ice (mln km$^2$) in the Arctic (a) and Antarctic (b) for different months (1–12) depending on the surface temperature (K) in the Northern (a) and Southern (b) hemispheres according to data for the period 1979-2020.

Table 1 presents quantitative estimates of the sensitivity of the total extent of Arctic and Antarctic sea ice $S_i$ [mln km$^2$] to the changes in the surface air temperature $T_P$ [K] in the Arctic and Antarctic for different months in interannual variability for the period 1980-2019. The parameters of sensitivity, estimated by the coefficients of the corresponding linear regressions, are significant within two standard deviations, as well as the corresponding correlation coefficients highlighted. In the Northern
Hemisphere, the estimates are statistically significant for all months. In the Southern Hemisphere, significant estimates (within two standard deviation) were obtained for most of the months.

**Table 1.** Estimates of the sensitivity of the total extent $S_I$ of the Arctic and Antarctic sea ice to changes in the surface temperature $T_s$ in the Arctic and Antarctic for different months by monthly-mean data in interannual variability (1980–2019).

| Months   | $dS_I/dT_s$ mln km$^2$ / K 1980–2019 | Arctic     | Antarctic  |
|----------|------------------------------------|------------|------------|
| January  | -0.28(±0.05)                       | -0.54(±0.27)|            |
| February | -0.25(±0.06)                       | -0.19(±0.14)|            |
| March    | -0.28(±0.06)                       | -0.69(±0.12)|            |
| April    | -0.31(±0.05)                       | -0.57(±0.12)|            |
| May      | -0.47(±0.08)                       | -0.34(±0.10)|            |
| June     | -0.90(±0.09)                       | -0.34(±0.11)|            |
| July     | -1.58(±0.22)                       | -0.23(±0.06)|            |
| August   | -1.63(±0.17)                       | -0.03(±0.08)|            |
| September| -1.17(±0.11)                       | 0.08(±0.10) |            |
| October  | -0.77(±0.05)                       | -0.08(±0.12)|            |
| November | -0.41(±0.04)                       | -0.45(±0.14)|            |
| December | -0.37(±0.05)                       | -0.80(±0.24)|            |

The highest (absolute) values of the sensitivity parameter $dS_I/dT_s$ for Arctic sea ice were estimated for the summer months (July and August) – up to -1.6 million km$^2$ with 1 K warming. The highest (absolute) value of the sensitivity parameter $dS_I/dT_s$ for Antarctic sea ice was also obtained for the summer season: -0.8 million km$^2$ with 1 K warming in December.

According to the data for recent decades, the negative correlation of the total Antarctic sea ice extent with the Antarctic surface air temperature is more significantly manifested, rather than with the surface air temperature of the Southern Hemisphere as a whole [27]. At the same time, the relationship between the interannual variations of sea ice extent and the surface air temperature for Antarctic region is more statistically significant, than for the whole Southern Hemisphere air temperature. Simultaneously, the relation of the interannual variations in Arctic sea ice extent to the hemispheric surface temperature is stronger than its relation to the regional temperature for most months of the year.

Figure 2 shows the dependence of the total extent of snow cover $S_S$ in the Northern Hemisphere for different months based on satellite data for the period 1979-2020 on the corresponding surface air temperature $T_S$ in the whole Northern Hemisphere based on the ERA5 reanalysis data. Considering stronger variations in the surface air temperature and the snow cover extent within the annual cycle, the corresponding interannual variations also appear in each different month. The sensitivity of the Northern Hemisphere snow cover $S_S$ to the changes in the Northern Hemisphere surface air temperature $T_S$ is determined by the coefficient of the corresponding linear regression. It is characterized by the straight line in Figure 2, and is estimated to be $-3.6$ million km$^2$ / K.
**Figure 2.** Dependence of the monthly mean total snow extent ($S_S$) in the Northern Hemisphere on the hemispheric-mean surface temperature ($T$) for the time interval 1979–2020.

Table 2 presents quantitative estimates of the sensitivity of the total snow cover extent $S_S$ [mln km$^2$] in Eurasia and North America to changes in the surface air temperature $T_C$ [K], respectively, in Eurasia and North America for different months in interannual variability for the period 1980–2019. The sensitivity parameters are estimated by the coefficients of the corresponding linear regressions that are significant within two standard deviations. The corresponding correlation coefficients are highlighted. A significant negative correlation between $S_S$ and $T_C$ is present for most of the month for Eurasia and North America.

**Table 2.** Estimates of the sensitivity of the total snow cover extent $S_S$ in Eurasia and North America to the corresponding changes of the surface temperature $T_C$ in Eurasia and North America by monthly-mean data for different months, 1980–2019.

| Months   | $dS_S/dT_C$, mln km$^2$ / K | Eurasia | North America |
|----------|-----------------------------|---------|---------------|
| January  | -0.52 ($±0.21$)             | -0.14 ($±0.07$) |
| February | -0.84 ($±0.13$)             | -0.25 ($±0.08$) |
| March    | -0.95 ($±0.15$)             | -0.34 ($±0.09$) |
| April    | -0.82 ($±0.23$)             | -0.83 ($±0.11$) |
| May      | -1.66 ($±0.24$)             | -0.67 ($±0.15$) |
| June     | -1.56 ($±0.27$)             | -1.07 ($±0.18$) |
| July     | -0.64 ($±0.12$)             | -0.40 ($±0.13$) |
| August   | -0.19 ($±0.07$)             | -0.08 ($±0.10$) |
The highest absolute value of the sensitivity parameter $dS/dT_c$ for Eurasia was obtained for May, which is $-1.7$ million km$^2$ for the increase in the surface air temperature in Eurasia by 1 K. The highest absolute value of the sensitivity parameter $dS/dT_c$ for North America was obtained for June, which is about $-1.1$ million km$^2$ for the increase in the surface air temperature in North America by 1 K.

In [50], based on the data on the annual variation for Northern Hemisphere, the sensitivity of the total extent of the snow-ice cover to changes in the surface air temperature was estimated in the range of $3.5\pm 5.1$ million km$^2$ / K. In this paper, the sensitivity of the total snow-ice cover extent of the Northern Hemisphere to changes in the hemispheric surface air temperature based on monthly average data for the same period is estimated equal to $-4.1$ million km$^2$ / K. At the same time, the sensitivity of the snow cover extent of the Northern Hemisphere to changes in the hemispheric near-surface temperature is estimated as $-3.6$ million km$^2$ / K for the period 1980–2019 ($-3.5$ million km$^2$ / K for the period 1980–1999 and $-3.7$ million km$^2$ / K for the period 2000–2019). The sensitivity of the extent of the Arctic sea ice to changes in the hemispheric surface air temperature was calculated at about $-0.7$ million km$^2$ / K for the period 1979–2020. This estimate was obtained under the condition of maximum correlation between the extent of the Arctic sea ice and hemispheric near-surface temperature variations. The lag of 1 month of the ice regime in the annual cycle relative to the temperature regime has been considered.

### 4. Conclusions

Interannual variations in the total extent of sea ice in the Arctic are statistically significantly associated with interannual variations in surface air temperatures both in the Arctic region and for the whole Northern Hemisphere in recent decades. At the same time, for most months of the year, the connection with hemispheric air temperature is manifested even more significant than a connection with regional temperature. Simultaneously, interannual variations in the total extent of sea ice in Antarctica are more statistically significantly associated with interannual variations in surface air temperature for Antarctic region than for the whole Southern Hemisphere.

For variations in the of snow cover extent in the Northern Hemisphere in recent decades, including Eurasia and North America, for most months, a significant negative correlation was noted with the corresponding interannual variations in surface air temperature. The negative correlation of the total snow cover extent on the continents of the Northern Hemisphere for most months is generally more significant with the continental surface temperature (for Eurasia and North America) than with the surface temperature for the Arctic latitudes and the whole Northern Hemisphere. At the same time, a more significant relationship between the total extent of the snow cover and the temperature in the corresponding Arctic sector is noted by the late spring – early summer. The weakening of statistically insignificant large-scale correlation between the snow cover and the temperature regime is manifested during the transition to the autumn season. At the same time, a statistically significant negative correlation of snow cover and the temperature in October-November was observed for the last two decades in the autumn months, particularly for Eurasia.

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