Determining the breaking points of the trend in long-term changes of air temperature in Barentsburg (Svalbard)

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Abstract

Changes in the average annual surface air temperature (SAT) in Barentsburg (Svalbard) for the period 1899-2022 are considered. The SAT increases at an average rate of 0.34°C/10 years. The warming process is not continuous and consists of two periods of cooling and two periods of warming. Statistical methods have been used to establish the most probable position of the breaking points of the SAT trend: 1917, 1938, and 1968. The recent ("modern") warming in the region began in the late 1960s, but since 1988, its intensity has doubled.

Key words: High Arctic, climate series, climate changes

***List of abbreviations*:** PELT – Pruned Exact Linear Time, SAT – surface air temperature, MS – meteorological station

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Introduction

Estimating the linear trend of the surface air temperature (SAT) time series is the simplest assessment of climate change and variability. However, a single linear regression for the entire study period does not describe the internal structure of the short-term changes within the time series, ignoring variations of the slope of the linear trend in individual sections of the series. Such trend changes (other scientific definitions: trend reversal or trend variations) include a change in trend from positive to

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negative (or vice versa), a change from a statistically significant trend to a statistically insignificant one (or vice versa), or a change in the magnitude of a trend while maintaining its sign.

A change in trend is an often (even inevitable) phenomenon in climate series. In practice, the trend breaking points, are usually detected approximately – most often visually using graphs of smoothed values. *I.e.*, in the work (ACIA 2005[1]), when analyzing SAT over the land surface in the Arctic zone (from 60° to 90° N) from 1900 to 2003, it was concluded that temperatures increased from 1900 to the mid-1940s, then it decreased until about the mid-1960s, and then increased again. For three periods (1900–1945, 1946–1965 and 1966–2003), approximately corresponding to successive warming-cooling-warming trends, linear trends of SAT anomalies were calculated. For the period 1946–1965 linear trends of SAT anomalies were negative, for other periods they were positive.

In the work of Førland et al. (2009), trends in SAT changes were determined over the entire period of instrumental measurements in Svalbard. The trends in average annual and average seasonal (calendar) SAT values in the archipelago were positive, with the exception of the meteorological station (MS) "Isfjord Radio". It was noted that trends in short time series depended on their starting and ending points. For example, for the Ny-Alesund MS, where the beginning of regular observations started in 1969, a positive trend was observed, while for the Isfjord Radio MS, where regular observations were carried out from the early 1930s to the end of 1976, the trend was negative. To compare trends across different periods, the study interval was divided into three 35-year periods with a 5-year overlap (1912–1946, 1942–1976, and 1972–present). The authors noted that in the first and last 35-year periods, the trends in SAT changes were positive, and in the period 1942–1976, most commonly, they were negative.

The work of Førland et al. (2011) examines the dynamics of SAT on Svalbard for MSs with the longest series of instrumental observations (Ny-Alesund, Svalbard Airport, Hopen, Bjørnøya). To compare linear trends in SAT changes, the entire studied interval was divided into four 23-year periods, within which several stations operated simultaneously: 1920–1942, 1943–1965, 1966–1988, and 1989–2011. In the first period (1920–1942), at two weather stations, linear trends in individual calendar seasons were negative (Svalbard Airport in summer, Bjørnøya in winter and spring), but in other calendar seasons and for average annual values they were positive. In the next period (1943-1965) at three MSs (Ny-Alesund, Svalbard Airport, Bjørnøya), SAT trends were generally negative for the calendar seasons, with the exception of positive trends in spring and summer at Ny-Alesund. For the average annual SAT values for the period 1943–1965, the trends were negative at all MSs. Over the last two periods (1966–1988 and 1989–2011), warming was observed at all MSs (Ny-Alesund, Svalbard Airport, Hopen, Bjørnøya) and in all seasons, with the exception of a slight cooling in the summer of 1966–1988 at Bjørnøya.

The work of Hanssen-Bauer et al. (2019), based on a visual analysis of SAT graphs smoothed with a Gaussian filter, provides a generalized picture of the climate of Svalbard: general warming until the 1930s, two relatively warm decades, a decrease in temperature from the 1950s to the 1960s and subsequent warming. Breaking points of the SAT trend were not established.

In the another work (Ivanov 2019), when studying changes in SAT in the area of the Svalbard archipelago for the period from 1900 to 2014 two periods of positive trends were identified: 1915–1935 and 1980–2009. SAT anomalies were calculated relative to the average value for the entire study period and smoothed using a moving average filter (11-year step). As the author's attention was focused on comparing periods of Arctic warming in the first half of the 20th century and modern warming, the periods with negative SAT trends were not considered.

Thus, in all of these works, the breaking points of the trends were determined approximately or formally.

It is quite obvious, that identifying breaking points of trend is an important part in the study of cause-consequence relationships in the climate system of the archipelago. However, traditional smoothing methods, for example, moving average, are not satisfying in identification of trend breaking points. A narrow smoothing window leaves many extremes in the series, each of which could be formally taken as a trend breaking point. As the smoothing window increases, the series becomes smooth, but loses some important information.

Objectively detecting the breaking points of the trend is quite a complicated computational task. Research on this topic is not sufficiently represented in the scientific literature. There is also no general standard for evaluating different trend change detection methods (Zuo et al. 2019).

The purpose of this work is to describe changes in SAT in Barentsburg (Svalbard archipelago) on various time scales and objectively identify trend breaking points.

Materials

In our study we used data from the Russian Research Hydro-Meteorological Institute – World Data Center (RIHMI-WCD) (Obninsk) and the Norwegian Meteorological Institute (Oslo), as well as a series of average monthly SAT in the Barentsburg prepared by the authors (Demin et al. 2020) started from December 1911.

Regular meteorological observations at Barentsburg began in August 1932 and, with a gap in the period 1941–1947, continue until the present. The SAT series in Barentsburg was extended until December 1911 based on observations made in 1911–1930 at the Norwegian MS “Spitsbergen Radio” (“Green Harbor”), located 1.5 km south from Barentsburg. Regression equations for reconstructing the SAT in Barentsburg for the period 1911–1931 were obtained during a number of parallel measurements organized in Barentsburg and on site of Norwegian MS “Green Harbor”, using two automatic weather stations (AWS) belonging to the Norwegian Meteorological Institute.

For other periods with no observations in Barentsburg, SAT values were calculated using data from the nearest stations located at Longyearbyen (37 km to the northeast) and on Cape Linné (MS “Isfjord Radio”, 14 km to the west), and during the period of complete absence of regular observations on the archipelago (1941–1947)- according to the NOAA CIRES Twentieth-Century Reanalysis (20CRv3). The periods of parallel operation of the Barentsburg, Isfjord Radio and Longyearbyen stations amount to tens of years. For the Barentsburg - Isfjord Radio pair, the period of parallel operation was 46-48 years, depending on the month. For the Barentsburg - Longyearbyen pair, common period was 28 years. The characteristics of the regressions were obtained from large samples, which suggests their reliability. The complete procedure for obtaining a composite series of SAT in Barentsburg since 1911 and checking its homogeneity is described in detail in Demin et al. (2020).

A series of SAT data obtained at the Svalbard Airport MS (Longyearbyen) is a reference one for studying climate change on Svalbard. It was restored to September 1898 (Nordli et al. 2020). In order to obtain comparable results, we extended the series in Barentsburg using linear regression equations between the monthly average SAT values at the Barentsburg and Svalbard Airport stations. The correlation of average monthly SAT between these MSs for the period of simultaneous operation (1975–2022) was 0.946-0.996, and for the average annual SAT (1976–2022) it was 0.993. The full list of MSs used to reconstruct missing SAT values in Barentsburg and the periods for which restoration was required are given in Table 1.

Periods with no observations at the Barentsburg MS	MSs, which data was used to restore SAT series at Barentsburg MS
September 1898 – November 1911	MC «Svalbard Airport»
December 1911 – August 1930	MS «Green Harbor»
September 1930 – December 1931	MS «Longyearbyen»
January 1934	MS «Longyearbyen»
August 1941 – November 1941	Reanalysis 20CRv3
December 1941 – June 1942	MS Longyearbyen
July 1942 – August 1945	Reanalysis 20CRv3
September 1945 – August 1946	MS «Longyearbyen»
September 1946 – November 1947	MS «Isfjord Radio»

Table 1. Periods with no instrumental observations at the Barentsburg MS and MSs which data was used to reconstruct SAT series at Barentsburg MS.

Due to the close location of the Barentsburg MS and the Svalbard Airport MS (36 km) and the close correlation of the corresponding SAT series, we can assume that the trends established at one of the MSs are also characteristic for the other. However, in this work we give preference to the SAT series in Barentsburg, because the share of original (not calculated, but measured) values in it is twice as large (at the location of the modern Svalbard Airport station, instrumental measurements of the SAT began only in August 1975).

Methods

In this work, the trend breaking points of average annual SAT values in Barentsburg were established by statistical methods. For this purpose, only significant changes in SAT were considered, determined by shifts in the average in the SAT series. Shifts were identified using the Sequential T-test Algorithm for Regime Shifts – STARS (Rodionov 2004) and Pruned Exact Linear Time – PELT (Jackson et al. 2005, Killick et al. 2012). The STARS algorithm is based on binary segmentation, where the first breaking point in a series is identified and it divides the data into 2 segments. Next, a similar search is performed in each segment separately. The procedure is repeated iteratively until no change is detected or the segments become smaller than the specified minimum length. The decision regarding the presence of a breaking point is made based on a t-test between segments. The minimum length of a segment is 10 years (it is hardly advisable to consider shorter periods, given the WMO recommendations for decennial updating of climate norms). The PELT algorithm is based on minimizing the “cost” (usually the sum of the residual variance) and "penalty" (model complexity) functions and is associated with an information criterion, the value of which depends on the number of breaking points used. In our work, we used the information criterion BIC – Bayesian Information Criterion.

To estimate the location of trend breaking points, an iterative algorithm was used, proposed in the work of Muggeo (2003) and implemented in the R "Segmented" software package (Muggeo 2008). We chose the R package "Segmented" because with its help, there are determined not only the positions of breaking points and the actual linear models for various segments, but also confidence intervals for all model estimates, including trend breaking points.

We used so-called trend filtering proposed in Kim et al. (2009). The filtered signal is represented by a set of straight lines without breaks – in the form of a continuous piecewise linear function. Long-term changes in SAT with this approach are represented in the form of a continuous piecewise linear model in which the data is segmented into the periods with a constant rate of change in SAT. We prefer simple linear forms because the trends used to account for nonlinear effects (polynomial regression, regression splines, and nonparametric smoothing) are not directly interpretable, even though they produce smooth lines with pronounced breaking points (Hastie and Tibshirani 1990).

Results

Determining trend breaking points in long-term changes in SAT in Barentsburg

Changes in the average annual SAT in Barentsburg for the period since 1898 (actual and reconstructed) are presented in Fig. 1. In general, over the entire study period (1899–2022), an increase in the average annual SAT was observed at an average rate of 0.34°C/10 years. This increase was not a continuous process and consisted of several periods of warming and cooling. The existence of these periods is clearly visible from the shifts of the average in the SAT series (*see* Fig. 1). Despite small discrepancy in determining the first shift at the beginning of the series (at the ends of the series any statistical tests are not entirely reliable), subsequently the segments determined by the STARS and PELT methods coincided. Both methods showed the existence of several periods (climatic regimes) in the dynamics of SAT:

1. Cold 1910s
2. Warm 1930-1950s
3. Cold 1960s
4. Warm period since 1970s and to the present time.

The resulting pattern of structural shifts of average in SAT series suggests the presence of three points in time when trend breaking points with changing trend sign should be observed: between 1910 and 1919 – change from cooling to warming, between 1930 and 1961 – change from warming to cooling, between 1960 and 1971 – change from cooling to new warming.

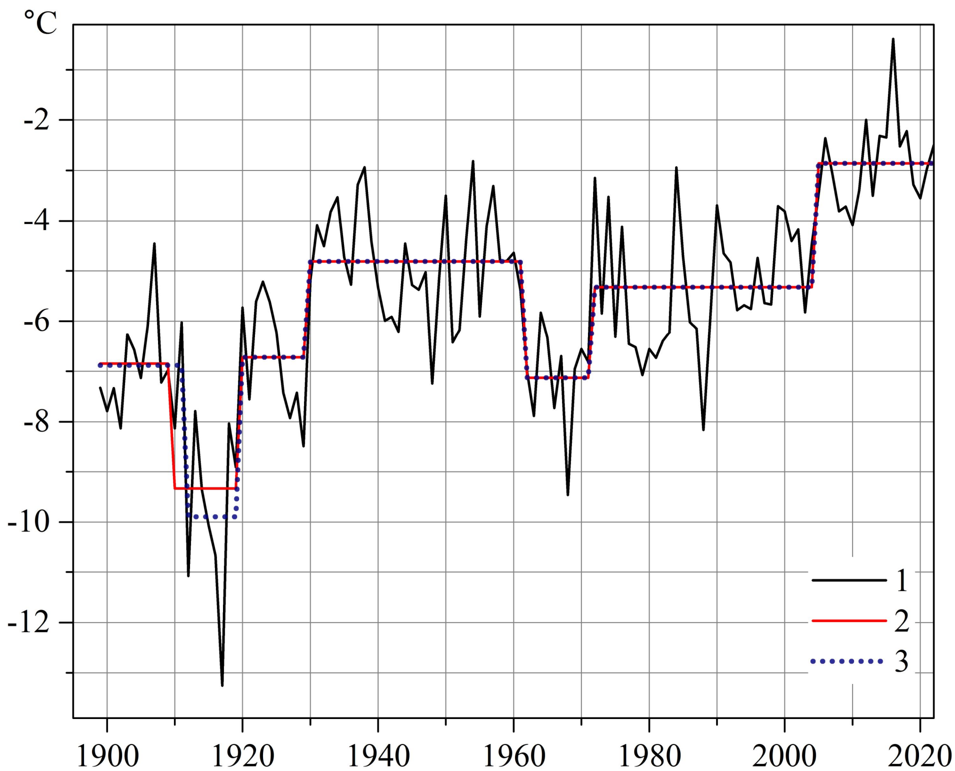

Fig. 1. Changes in average annual SAT values (1) and structural shifts in the thermal regime determined by the PELT (2) and STARS (3) methods for the period 1899-2022.

The R package "Segmented" was used to establish these moments. It determined years when a trend changes were observed: 1916, 1934 and 1968. The continuous piecewise linear trend corresponding to these points is shown in Fig. 2a. Even without additional estimates (visually), it is clear that the piecewise linear trend provides a better fit to the observed changes in SAT than the general trend for the period 1899–2022. The last period (1968–2022) - the period of warming – turns out to be quite long. It is difficult to admit that throughout its entire length the rate of SAT growth did not change. The presence of such a breaking point is also indicated by works showing an increase in modern warming, both on a global (Karl et al. 2000) and regional scale (Karandasheva et al. 2021). The results of calculations, assuming the existence of a 4th breaking point, showed increased warming in 1988 or 1994 (*see* Fig. 2b, c). The ambiguity may thave arised from the fact that all tests of trend change work well when adjacent periods have different trends in sign, but become less reliable when the trend maintains sign but changes in magnitude. In the first option (breaking point in 1988), the warming rate changed from 0.037 to 0.104°C/year (2.8 times), in the second (breaking point in 1994) – from 0.047 to 0.114°C/year (2.4 times). The change in trend slope in 1988 was slightly larger. For this reason, any test for changes in regression slope applied separately to the period 1968–2022 would give 1988 as the breaking point.

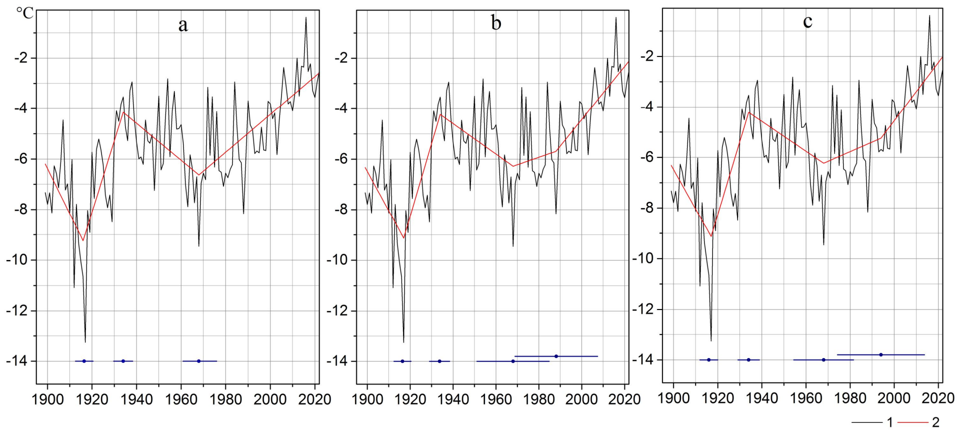

Fig. 2. Average annual SAT in the Barentsburg (1) and piecewise linear trend (2); horizontal blue lines – 95% confidence interval for finding breaking points. *Note*: **a** – breaking points with changing trend sign, **b** – breaking point based on the trend value (1988), **c** – breaking point based on the trend value (1994).

Noteworthy is the significant error in establishing the dates of trend breaking points (*see* Fig. 2). The dates of the changes in magnitude (1988 or 1994) are determined with a larger error than the dates of the change in sign. At the same time, the introduction of 1988 or 1994 into the model worsened the reliability of determining the nearest breaking point by sign, as can be seen from the expansion of the 95% confidence interval for 1968.

We decided to check our estimates in another way, using the method proposed in Kim et al. (2009). Initially, no assumptions are required about the number and position of breaking points. Within the framework of the method, the parameter λ is estimated, which is a measure of the smoothness of the trend and is selected experimentally: at λ→0. The filtered signal repeats the actual series, as λ increases, the number of breaking points decreases, and at λ→∞, the method will give a general linear trend for the entire series without breaking points. By operating with λ, one can achieve the desired proximity of the original and filtered signal. Various options for the trend of the average annual SAT with different values of λ are shown in Fig. 3. As λ decreased, the detailing increased. We decided to put a limit to the minimum value λ=16, since at lower values of λ short periods with trend changes (about 10 years or less) arose, which we would like to avoid. At λ=16, three trend breaking points in sign were found in the series, and they coincided with those calculated earlier: 1916, 1934 and 1968. A trend breaking point towards greater cooling appeared in 1956. There remained uncertainty about the breaking point towards greater warming between 1988 and 1994. The breaking point in 1988 was found in a wide range of λ, while the breaking point in 1994 appeared only at λ=16-22.

The dates for the breaking points of the SAT trend were obtained using statistical methods. It is advisable to compare them with the actual picture and, if necessary, make clarifications to the calculated points for the best fit of the model.

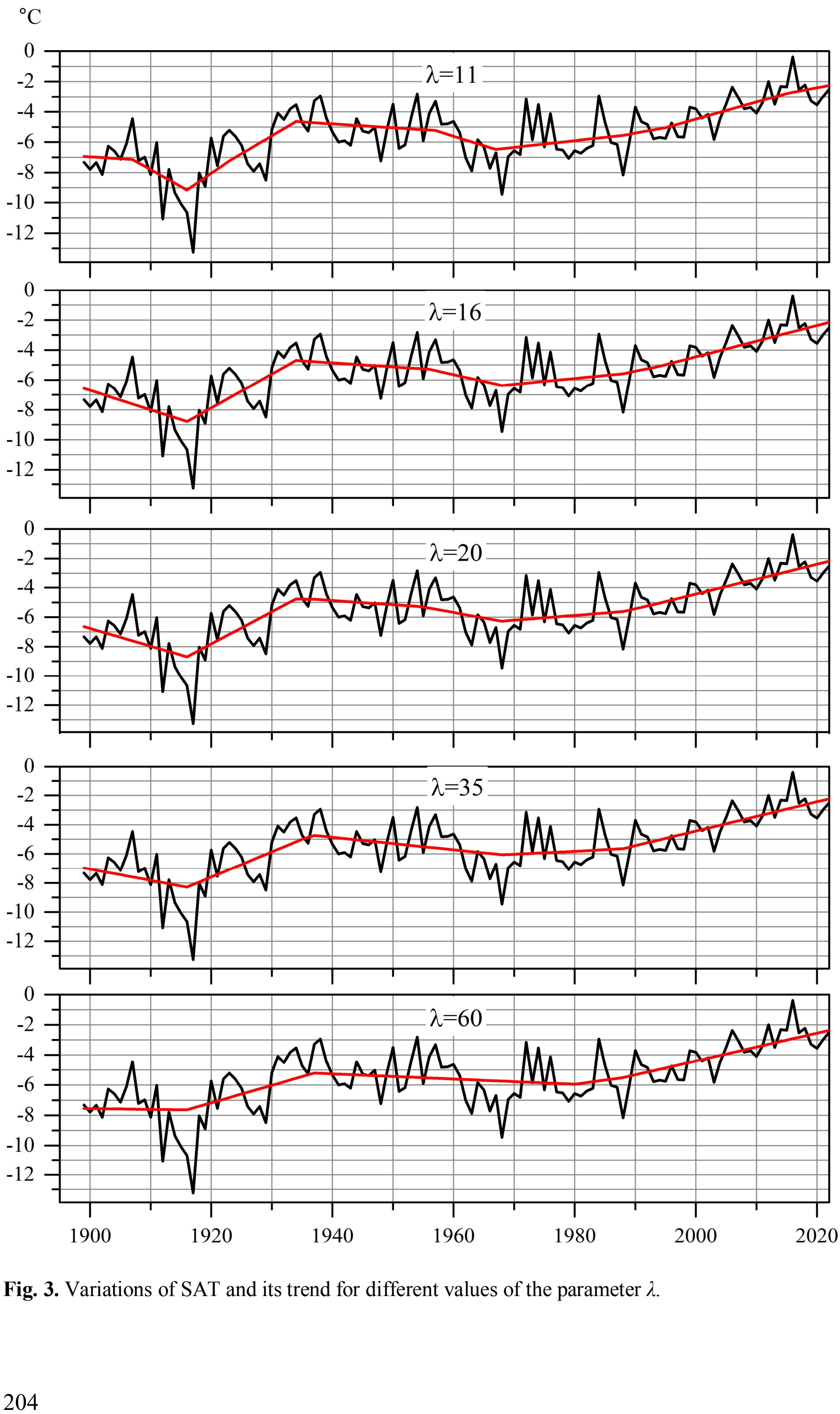

Fig. 3. Variations of SAT and its trend for different values of the parameter *λ*.

Statistical methods showed that the first breaking point in the SAT trend occurred in 1916 or 1917 – cooling gave way to warming, which is close to reality. In 1917, the average annual SAT in Barentsburg reached its minimum value for the entire period of instrumental observations and amounted to -13.3°C. In 1918, anomalies of average monthly SAT compared to the previous period (1911–1917) were positive in 10 out of 12 months. The increase in SAT that followed 1917 was a manifestation of the so-called “first” warming of the Arctic in the 20th century.

According to statistical tests, the second trend breaking point of changes in SAT occurred in 1934 – warming gave way to cooling. In our opinion, the turning point should be considered not 1934, but 1938. Firstly, 1937 and 1938 were the warmest years of the “first” warming period of the 20th century. Secondly, 1938 was indicated as a breaking point by analyzing the number of months with a positive anomaly in the monthly mean SAT. In 1934, there was a positive anomaly of average monthly SAT (relative to the average values for the previous period 1924–1933) in 11 months out of 12. In 1935 there were 8 such months, in 1936 – 9, in 1937 – 11, in 1938 – 10 months. In subsequent years, the number of months with a positive anomaly relative to the previous decade decreased rapidly. In 1939 there were 7 of them, in 1940 - 3, in 1941 - 4, in 1942 - 2, in 1943 - 3 months. A large number of months with a positive SAT anomaly suggested that the period 1935–1938 should be seen as a continuation of the warming that began in 1917, and not the beginning of a period of cooling. 1938 year was included within the 95% confidence interval of the breaking point in 1934, determined analytically (*see* Fig. 2). The cooling began in 1939 and continued until the late 1960s. The minimum value of SAT was observed in 1968. Statistical methods also point to 1968 as a breaking point. Since 1969 SAT values have been increasing, a positive trend appeared, and we can talk about new warming.

During the cooling of 1939–1968 a trend breaking point towards increasing cooling was revealed in 1956. It would be more correct to take 1957 as a breaking point, as in 1957 the SAT was higher than in 1956, and in subsequent years (until 1971) the SAT values were lower than in 1957. The noted year 1957 broke period 1938–1968 into two separate subperiods: 1938–1957, when a weak cooling trend was observed, and 1957–1968 with a pronounced decrease in SAT. The period 1957–1968 turned out to be quite short (12 years) and, perhaps, in a simpler model, the entire period 1938–1968 should be considered as a single period of cooling without internal detail.

Identification of the breaking point in 1988 in the direction of increased warming can be considered more justified, since the periods before (1968–1988) and after (1988 –2022) were quite long, and the rate of warming at their border increased by 2 times. From a physical point of view, it seems more correct to speak of an increase of modern warming (which began in 1969) between 1988 and 1994.

It should be noted that the adjusted dates of trend breaking points in none of the cases fall outside the 95% confidence interval for dates determined by statistical methods.

General scheme of changes in SAT in Barentsburg in the period 1898–2022 with the breaking points of the long-term trend, established by statistical methods and taking into account the real picture of changes in SAT, is presented in Fig. 4.

Various options for trend breaking points in SAT in Barentsburg, determined by statistical methods and adjusted taking into account actual changes in SAT, are shown in Table 2. An assessment of the reliability of the model using the coefficient of determination (R^2) showed that adding additional breaking points in magnitude to the breaking points in sign did not improve its quality. The reliability of the model remained at the same level, but it opened up the possibility of a more detailed analysis of SAT changes.

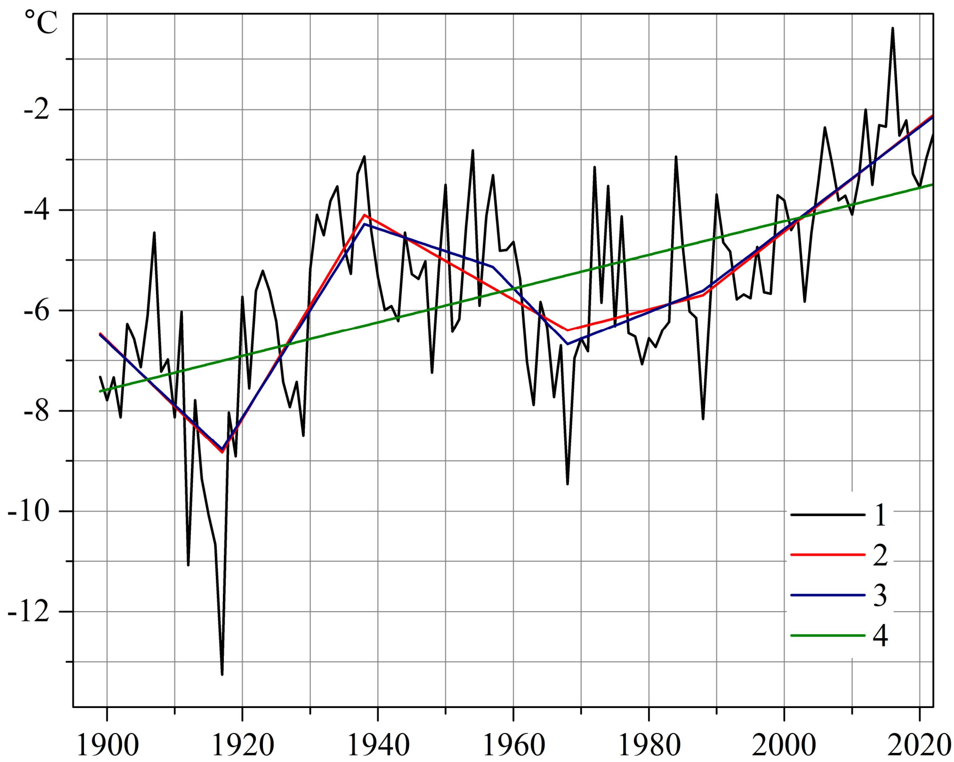

Fig. 4. Long-term changes of SAT in Barentsburg.
Note: 1 – average annual values, 2 – piecewise linear trend with 4 breaking points (1917, 1938, 1968, 1988), 3 – piecewise linear trend with 5 breaking points (1917, 1938, 1957, 1968, 1988), 4 – general trend.

Years of trend breaking points	R^2	Rates of SAT changes during periods of cooling and warming (°C/year)
1916, 1934, 1968	0.58	-1.78, 2.82, -0.73, 0.75
1917, 1938, 1968	0.57	-1.34, 2.32, -0.91, 0.78
1917, 1938, 1968, 1988	0.58	-1.31, 2.25, -0.77, 0.37, 1.04
1917, 1938, 1968, 1994	0.58	-1.32, 2.26, -0.78, 0.47, 1.14
1917, 1938, 1957, 1968, 1988	0.59	-1.26, 2.13, -0.45, -1.39, 0.53, 1.02

Table 2. Models of a continuous piecewise linear trend of SAT in Barentsburg with a different number of trend breaking points.

Discussion

As mentioned above, the presence of breaking points in long-term series of SAT on Svalbard was noted by a number of researchers (Førland et al. 2009, 2011; Hanssen-Bauer et al. 2019, Ivanov 2019), but the position of these points was determined formally or approximately. The time intervals of trends of different signs in SAT changes identified in this work were compared in Table 3 with the time intervals of trends determined in the above works.

Source	Trend signs				
	–	+	–	+	+
Demin et al. (this work)	1899-1917	1917-1938	1938-1968	1968-1988	1988-present
ACIA 2005[1]		1900-1945	1946-1965	1966-2003	
Førland et al. 2009		1912-1946	1942-1976	1972-present	
Førland et al. 2011		1920-1942	1943-1965	1966-1988	1989-2011
Hanssen-Bauer et al. 2019		1900s-1950s	1950s-1960s	1960s - present	
Ivanov 2019		1915-1935		1980-2011	

Table 3. Time intervals of trends of different signs in long-term changes of average annual SAT values.

Earlier work (ACIA 2005[1]) showed that the Arctic climate in the 20th century included three main periods. The first and last showed a statistically significant warming, while the intermediate period showed a statistically significant cooling. Accordingly, even the formal division of the studied SAT time series for Svalbard assumed the presence of a cooling time interval between warming intervals. Thus, in well-known works (Førland et al. 2009, 2011) the study period was divided into equal intervals: in the first case, these are intervals of 35 years, in the second, 23 years. In both cases, an interval was identified in the middle of the 20th century in which SAT trends are negative (*see* Table 3).

In the works (Hanssen-Bauer et al. 2019, Ivanov 2019), the time intervals of warming/cooling were determined visually using SAT charts. While in the work (Hanssen-Bauer et al. 2019) the boundaries of the time intervals were approximate, then in the work (Ivanov 2019) the boundaries were defined more precisely. It should be noted that the climate of the first third of the 20th century in these works was studied using the only SAT series covering this period – the composite SAT series for the Svalbard Airport MS. At the same time, the work of Ivanov (2019), in contrast to the work of Hanssen-Bauer et al. (2019), assumed the presence of a cooling at the very beginning of the 20th century (cold 1910s), because the beginning of the period with a positive SAT trend dated back to 1915.

A comparison of estimates showed a certain consistency of all results: the presence of two periods of warming separated by a period of cooling. The greatest similarity in the position of the breaking points of the SAT trend identified in this study was observed with the results of Ivanov (2019) obtained for the first half of the 20th century. The transition from the cooling of the early 20th century to the “first” warming was marked in this work and in (Ivanov 2019) in 1917 and 1915, respectively; the transition from the "first" warming to the cooling of the 1960s was marked in 1938 and 1935, respectively. Therefore, the visual analysis was confirmed by the results obtained by statistical methods.

Unlike the works of other researchers, who used approximate and/or formal approaches (graphical method and/or dividing the entire series into equal periods) to determine breaking points, our study proposed a statistically based approach using a continuous piecewise linear trend. This approach made it possible to determine more accurately the position of the breaking points of SAT trends both by the sign and the magnitude of the trend slope. It will be interesting to compare the dates of the SAT trend breaking points discovered in this work with the dates of trend breaking points of a number of other parameters (hydrological, oceanological, *etc.*) to establish cause-consequence relationships.

Conclusions

Changes in average annual SAT in Barentsburg for the period 1899–2022 were analyzed. During the study period, the general increase in the average annual SAT occurred at a rate of 0.34°C/10 years. This increase was not a continuous process. Two periods of cooling and two periods of warming were distinguished in the series of SAT.

Most reliably, we detected the dates of trend breaking points with changing trend sign: 1917, 1938, 1968. Two breaking points of quantitative change in the trend were also discovered while trend maintaining its sign: in 1957 (increased cooling) and in 1988 (increased warming).

In the period 1899-1917 in the study region, cooling was observed at an average rate of -1.3°C/10 years, which was replaced by rapid warming at a rate of about 2.2°C/10 years. The first warming should include the period 1917-1938. This was followed by a slight cooling (less than -0.1°C/10 years), which in 1957 intensified to -1.4°C/10 years. Since 1969, a gradual increase in SAT and a new climate warming began. Since 1988, the rate of warming of the average annual SAT in Barentsburg has almost doubled.

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