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Estimation of tendencies, homogeneity and stationarity of air temperature at the Ukrainian Antarctic «Akademik Vernadsky» station during 1951—2020

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In this paper results of the complex analysis of surface air temperature tendencies investigations at the Ukrainian Antarctic Akademik Vernadsky station are represented. Antarctica is a region that has a high rate of surface air temperature increase. The Antarctic Peninsula has experienced particularly fast warming, which has the highest temperature rise in the Southern Hemisphere. Therefore, in Antarctica, the study of surface air temperature change is important.

The Ukrainian Antarctic Akademik Vernadsky station is located on Galindez Island near the Antarctic Peninsula. Investigation of the surface air temperature is especially relevant to the Akademik Vernadsky station, because it has difficult conditions for its formation. The research goal is the estimation of tendencies, homogeneity and stationarity of the annual and mean monthly values of surface air temperature at the Ukrainian Antarctic Akademik Vernadsky station based on a combined approach with the use of several statistical and graphical methods. The use of various statistical methods that differ in characteristics (sensitivity to the law of distribution, autocorrelation, etc.) allows obtaining more reliable estimates. Graphic methods give an opportunity to analyze the tendencies over time and its change periods, the cyclical fluctuations and their characteristics (phases of increase and decrease, their duration, synchronicity, in-phase). Therefore, 4 statistical tests (standard normal Alexandersson test, Buishand test, Pettitt test, von Neumann relation) and 2 graphical methods (mass curve and residual mass curve) were used in the study.

At the Ukrainian Antarctic Akademik Vernadsky station, the observation series of the mean annual air temperature are quasi-homogeneous and quasi-stationary, as it has only a cooling phase and a warming phase of long-term cyclical fluctuations, which are also unfinished. The transition from the cooling phase to the warming phase took place in 1982. Tendencies in mean monthly air temperatures are similar to tendencies in mean annual temperatures. The differences are only for some months, namely, for the period from September to December.

Key words: air temperature, cyclical fluctuations, stationarity, homogeneity, Antarctica, statistical tests, graphic methods.

Introduction. In Antarctica, the research of surface air temperature change is important because its tendencies directly affect change of the area and mass of the glacier [Franzke, 2013; Chernov et al., 2021]. In turn, increasing or decreasing the ice cover directly affects the global circulation of the atmosphere and the level of the world's oceans [Turner et al., 2016; Diener et al., 2021]. Antarctica is a region that has a high rate of surface air temperature increase. The Antarctic Peninsula has experienced particularly rapid warming [Barrand et al., 2013; Cape et al., 2015]. The Ukrainian Antarctic Akademik Vernadsky station is located on Galindez Island near western coast the Antarctic Peninsula. Observation series from this station are used in many research to analysis of surface air temperature trends [Martazinova et al., 2010; Franzke, 2013; Tymofeyev, 2013; Gonzalez, Fortuny, 2018;

Turner et al., 2020]. At the same time, with the lengthening of the observation series over time and equipment replacement, etc., there is a need to analyze their homogeneity and stationarity. On the Akademik Vernadsky station for the surface air temperature such analysis is especially relevant, because its has difficult conditions for its formation [Martazinova et al., 2010; Tymofeyev, 2013]. In addition, the analysis of the homogeneity and stationarity of the observation series is an extremely important step of any study, as the choice of further methods and directions of research depends on the results obtained [WMO, 1990, 2018; Yozgatligil, Yazici, 2016; Gorbachova et al., 2018]. The presence of inhomogeneity in the series may be due to both natural and methodological reasons (relocation of the observation gauges, change in the number or time of observations, replacement of devices, etc.) [WMO, 1990]. In addition, such research is very relevant in view of climate change, which also can cause a breach of the homogeneity and stationarity of observation series [McCarl et al., 2008; Jaiswal et al., 2015; Yozgatligil, Yazici, 2016; Hamdi et al., 2018]. To obtain reliable results it is very important to apply an integrated approach based on the use of different methods [Gorbachova, Bauzha, 2013; WMO, 2018; Zabolotnia et al., 2022].

This study based on a combined approach is used, which consists in the use of several statistical and graphical methods the tendencies, homogeneity and stationarity of air temperature in the Ukrainian Antarctic Akademik Vernadsky station during 1951—2020 examines. This approach has not been used in research before.

The study area. The Ukrainian Antarctic station Akademik Vernadsky (until 1996 it was the Faraday station, Great Britain) is located off the western coast of the Antarctic Peninsula on Galindez Island, Argentine Islands Archipelago (Fig. 1). In the area of the Akademik Vernadsky station, the meridional orientation of the coastline largely determines the regime of air flows (along the coast). At the same time, the mountain system of the Antarctic Peninsula, which has an average plateau height of up to 2000 m above the sea level (the height of individual island peaks reaches 2800 m) forms the foehn wind [King, Tuner 1997]. Cooling of the air over the ice cover forms the local scale winds. All these processes have a significant effect on the air temperature regime at the Akademik Vernadsky station [Martazinova et al., 2010; Tymofeyev, 2013].

The Galindez Island has the marine subarctic climate type [King, Tuner, 1997; Franzke 2013]. In the Akademik Vernadsky station area the short snowfalls and snowstorms are often observing. Anticyclones are observed rare and case the calm frosty weather, sometimes with fog [King, Tuner, 1997].

For the period 1951—2020 on the Akademik Vernadsky station January was the warmest month of the year with a multi-annual mean monthly temperature +0.8 °C, August was the coldest month of the year with a multi-annual mean monthly temperature –8.7 °C. In the February was observed the highest mean monthly air temperature is +2.4 °C and in the July was observed the lowest mean monthly air temperature is –20.1 °C [Khrystiuk et al., 2022].

Methodology and data. The first stage of the research is to check the air temperature observation series on the absence of observation gaps and gross (mechanical) errors. The air temperatures observation series were also tested for emissions that exceeded four standard deviations from the mean daily air temperature. Such procedures control the quality of observation data.

To assess the homogeneity and stationarity of surface air temperature series, a combined approach is used, which consists in the use of several statistical and graphical methods. The use of different statistical methods that differ in characteristics (sensitivity to the law of distribution, autocorrelation, etc.) allows to obtain more reliable estimates [WMO, 1990; Gorbachova, 2014; Gorbachova et al., 2018]. Graphic methods allow an opportunity to analyze the tendencies over time and its change periods, the cyclical fluctuations and their characteristics (phases of increase and decrease, their duration, synchronicity,

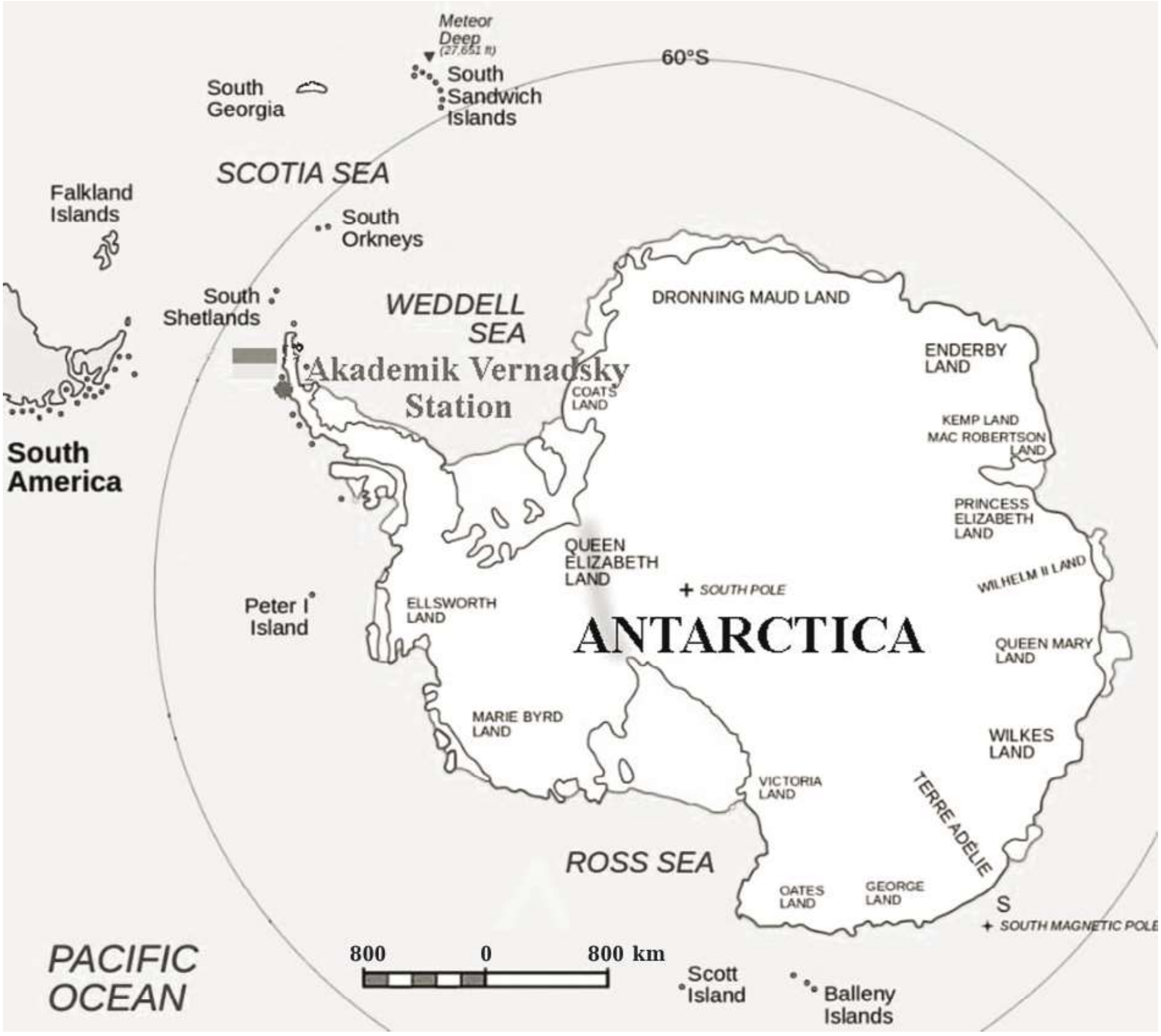

Fig. 1. Location of the Ukrainian Antarctic Akademik Vernadsky station.

in-phase) [Gorbachova, 2016; WMO, 2018].

Among the statistical tests four were selected for the research. They are most often used to assess the homogeneity of observation series and are recommended by the WMO guidelines [WMO, 1990, 2018]:

- standard normal Alexandersson test;
- Buishand test;
- Pettitt test;
- von Neumann relation.

The stationarity of time series indicates that their statistical characteristics (mean, variance) do not change over time. There is no time trend in the stationary series.

In the investigation of establishing the trend equation in the time series, as well as the correlation coefficient between variables was determined by the Pearson method. Estimation of trend statistical significance was carried out the using of nonparametric Mann-Kendall test [WMO, 2018].

Statistical processing of observation series were carried out in the software R language. In this case, *RStudio* version 1.4.1717 was used with following functions: pettitt.test, br.test, snh.test, VonNeumannTest, MannKendall, gml, cor.test [R Core Team, 2017].

Graphic analysis of homogeneity and stationarity assessment of observation series is based on the use of methods that have become widely used in hydrometeorological research. Such methods include a variety of correlation plots, frequencies, histograms, mass curve, double mass curve, residual mass curve, chronological graphs, etc. [WMO, 1990; Gorbachova, 2016]. Many researchers prefer the mass curve analysis, double mass analysis, as well as residual mass curve [Gorbachova, 2016]. The development and application of these methods in hydrometeorological research began at the end of the 19th century. In 1883, W. Rippl published his research to determine the optimal capacity of the reservoir and, accordingly, the «ideal» height of the dam, in which he invented the method of mass curve and residual mass curve [Rippl, 1883]. Later, Schoklitch A. (1923) and Novotny J. (1925) developed methodological knowledge about these methods [Klemeš, 1987]. During a research of precipitation time series and river runoff, the American scientist Merriam C. invented the method of double mass curve in 1937 [Merriam, 1937]. During the XX century, the main methodological approaches to the application of the mass curve, double mass curve and residual mass curve methods were developed by such scientists as Kohler M., Weiss L. & Wilson W., Searcy, J. & Hardison C., Ehlert K. et al. [Kohler, 1949; Weiss & Wilson, 1953; Searcy & Hardison, 1960; Ehlert, 1972]. Modern methodological approaches to assessing the homogeneity and stationarity of observation series using graphical methods developed by Gorbachova L. [Gorbachova et al., 2018; Gorbachova, 2014, 2016, 2017; Zabolotnia et al., 2019]. Two graphical methods were used in this research, namely the mass curve and the residual mass curve.

According to the mass curve, the cumulative values of the hydrometeorological characteristic under constant conditions of its formation approach the graph in the form of a straight line, the slope of which relative to the abscissa axis is constant over time. The deviation of the hydrometeorological characteristic from the straight line on the graph is an indicator of its changes and, accordingly, changes in the conditions of its formation [Gorbachova, 2017]. Short- and long-term cyclic fluctuations can be investigated by the residual mass curve [Andreyanov, 1959; Gorbachova, 2017]. The residual mass curve is a graph of successively accumulated deviations of a hydrometeorological value from its specific initial value, for example, an arithmetic mean, depending on time or dates.

The database of the State Institution «National Antarctic Research Center» of the Ministry of Education and Science of Ukraine to assess the homogeneity and stationary annual and mean monthly values of surface air temperatures for the period 1951—2020 was used.

Results and discussion. During the 70-year observation period, in the observation series for air temperature the gross errors or significant emissions were not detected. The coldest year was 1959 with a mean annual air temperature of –8.10 °C, and the warmest year was 1989 with a mean annual air temperature of –1.20 °C. The multi-annual mean annual air temperature is –3.6 °C.

Analysis of the application of four statistical tests to assess the homogeneity of the mean annual values of surface air temperature to the station Academician Vernadsky showed that all four tests indicate the heterogeneity of the series, because the values of statistics exceed the critical values (Table 1). Disturbance of homogeneity occurred in 1982. For

Table 1. The results of checking homogeneity of mean annual surface air temperature observation data on the Akademik Vernadsky station, 1951—2020

Test	The value of statistics	Year of disturbance of homogeneity	*p*-value
Alexandersson	24,5	1982	<0,0001
Buishand	2,47	1982	<0,0001
Pettitt	840	1982	<0,0001
von Neumann	0,80	—	<0,0001

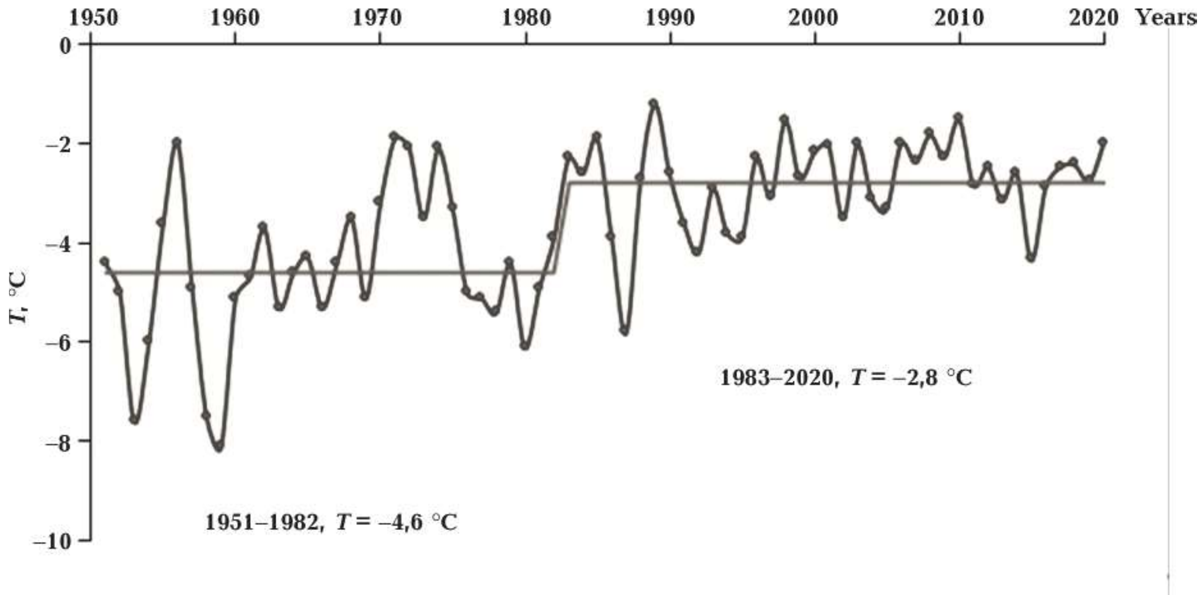

Fig. 2 Mean annual values of surface air temperature on the Akademik Vernadsky station, 1951—2020.

the period 1951—1982 the average value of air temperature is –4.6 °C, and for the period 1983—2020 is –2.8 °C (Fig. 2).

Statistical tests also unequivocally indicate a disturbance of the homogeneity of the series of mean monthly values of surface air temperature in February (1970) and June (1981) (Table 2, Fig. 3). In other months of the year there is no unambiguous assessment of homogeneity, because tests indicate different years of homogeneity disturbance or the calculated values of the criteria do not exceed the critical.

The Mann-Kendell statistical test was used to assess the stationarity of observation series. Analysis of the results showed that in all series of surface air temperatures revealed statistically significant trends at a significance level of 1 % except for the series of mean monthly temperatures for September-December (Table 3).

Thus, when assessing the homogeneity and stationarity of the mean monthly surface air temperature according to statistical tests, there are difficulties with interpreting the results. Therefore, for a clearer understanding and confirmation of the results of statistical tests the graphical methods of the assessment of the homogeneity and stationarity of observation series were used.

The constructed mass curve of the mean annual surface air temperature at the Akademik Vernadsky station for the period 1951—2020 showed that the mass values of the mean annual air temperature deviate from the straight line and seem to form a view of arc, then cross the straight line and form an arc again (Fig. 4, *a*). Such view of mass curve indicates the absence of a one-way steady tendency. Thus, the appearance of the mass curve indicates that the observation series have an inflection point, after which the tendency of the mean annual air temperature changes. The analysis of the residual mass curve showed that in 1982 there was a transition from the phase of decrease (cooling) of the mean annual air temperature to the phase of its increase (warming), which continues until now and the end of which cannot be predicted (Fig. 4, *b*).

As noted in the papers of Andreyanov V. [1959], Gorbachova L.O. [2017] the different phases of cyclic fluctuations have different characteristics: in the phase of increase the values are much larger than the values observed in the phase of decrease. As a result, these phases of cyclic fluctuations have a significant difference in the mean values. This means that according to statistical tests, such a series will be classified as inhomogeneous (see Table 1). Therefore, the presence in the observation series of the mean annual surface

T a b l e 2. The results of checking homogeneity of mean monthly surface air temperature observation data on the Akademik Vernadsky station, 1951—2020

Results of test	Alexandersson test	Buishand test	Pettitt test	von Neumann relation
January				
Year of homogeneity disturbance	1970	1982	1982	—
The value of statistics	18,04	2,06	691	1,58
p-value	0,0002	0,0014	0,0005	<0,0001
February				
Year of homogeneity disturbance	1970	1970	1970	—
The value of statistics	19,64	2,00	644	1,47
p-value	<0,0001	0,0017	0,0016	<0,0001
March				
Year of homogeneity disturbance	1970	1970	1981	—
The value of statistics	15,76	1,84	589	1,58
p-value	0,0014	0,0083	0,0050	<0,0001
April				
Year of homogeneity disturbance	1960	1970	1993	—
The value of statistics	14,00	1,68	434	1,35
p-value	0,0040	0,0280	0,0777	<0,0001
May				
Year of homogeneity disturbance	1960	1981	1981	—
The value of statistics	20,20	2,08	843	1,01
p-value	0,0001	0,0012	<0,0001	<0,0001
June				
Year of homogeneity disturbance	1981	1981	1981	—
The value of statistics	18,69	2,15	755	1,20
p-value	0,0002	0,0006	0,0001	<0,0001
July				
Year of homogeneity disturbance	1987	1987	1982	—
The value of statistics	16,31	2,02	678	1,18
p-value	0,0006	0,0023	0,0007	<0,0001
August				
Year of homogeneity disturbance	1981	1982	1982	—
The value of statistics	18,99	2,24	730	1,21
p-value	0,0002	0,0003	0,0002	<0,0001
September				
Year of homogeneity disturbance	1987	1987	1987	—
The value of statistics	7,55	1,38	442	1,71
p-value	0,1019	0,1600	0,0688	<0,0001
October				
Year of homogeneity disturbance	1994	1994	1994	—
The value of statistics	10,73	1,59	513	1,72
p-value	0,0192	0,0476	0,0214	<0,0001
November				
Year of homogeneity disturbance	1982	1982	1982	—
The value of statistics	6,25	1,41	375	1,69
p-value	0,1870	0,1366	0,1769	<0,0001
December				
Year of homogeneity disturbance	1962	1968	1968	—
The value of statistics	9,63	1,83	437	1,83
p-value	0,0338	0,0089	0,0743	0,0004

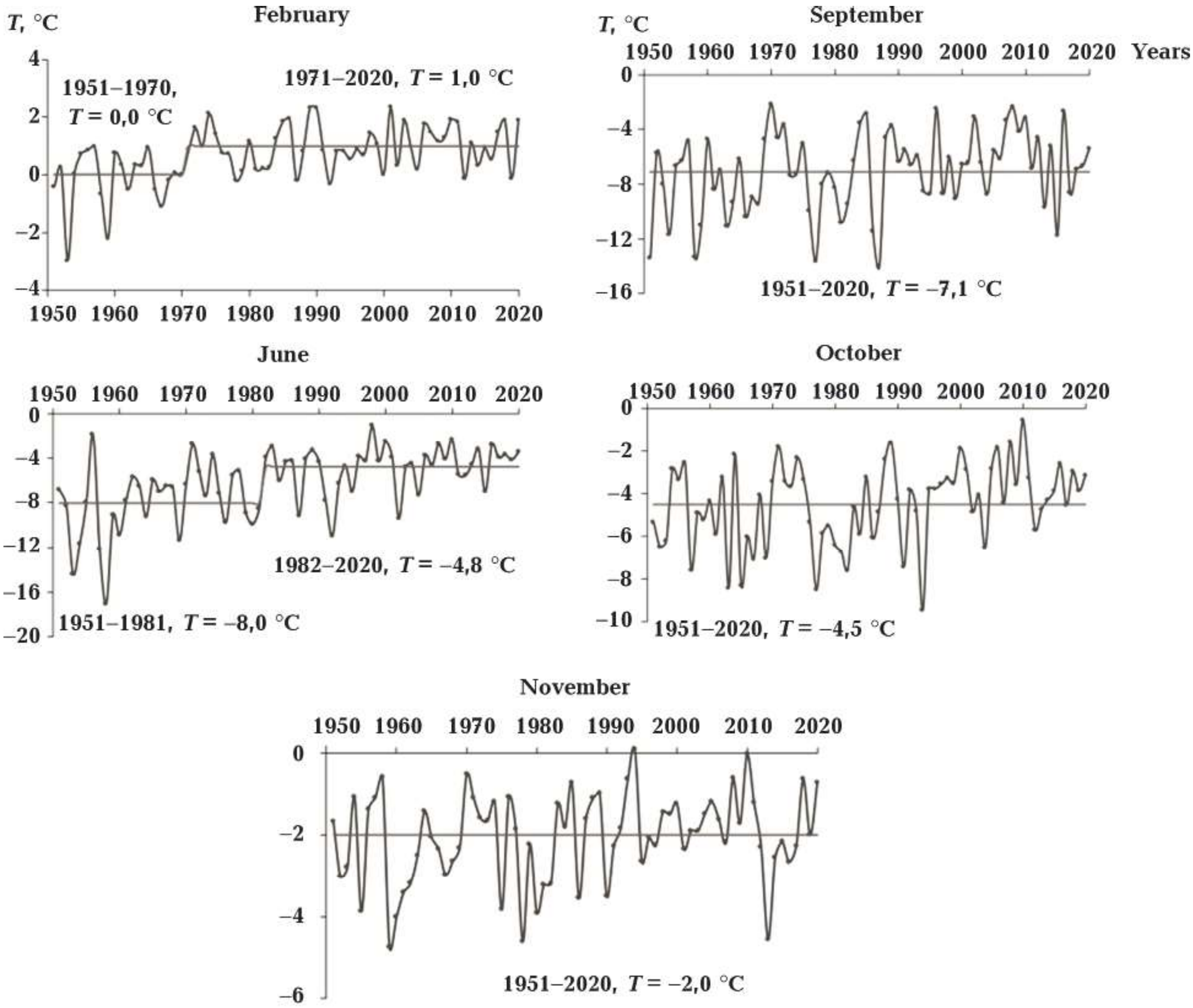

Fig. 3. Mean monthly surface air temperatures for individual months on the Akademik Vernadsky station, 1951—2020.

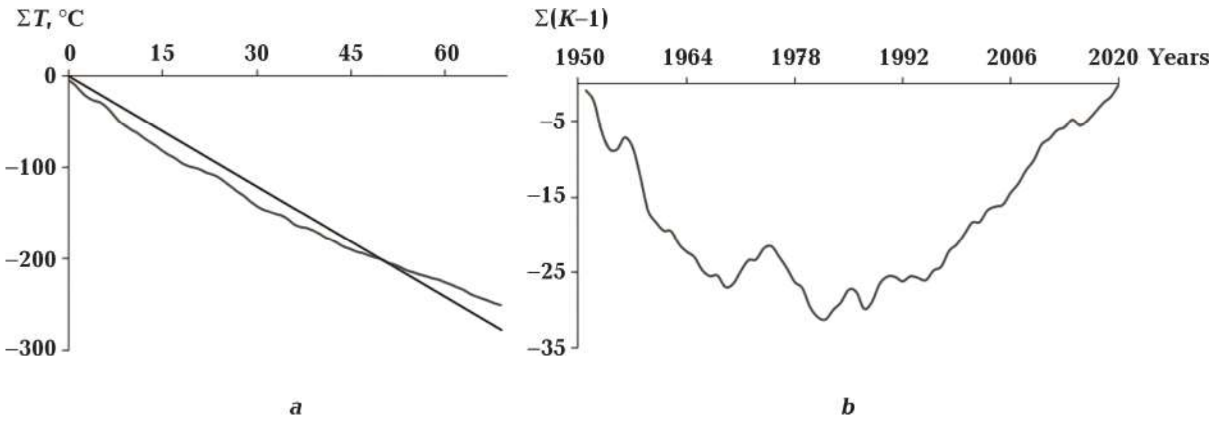

Fig. 4. Mass curve (*a*) and residual mass curve (*b*) of the mean annual surface air temperature on the Akademik Vernadsky station, 1951—2020.

air temperature only the cooling phase and the warming phase of cyclic fluctuations and forms to sinuous type of the mass curve with an oscillating deviation of the mass values

Table 3. The checking results of surface air temperature series for stationarity according to the Mann-Kendell test, Academician Vernadsky station, 1951—2020

Surface air temperature	Trend equation	Correlation coefficient	τ	p-value	Statistical significance of the trend
Mean annual	y=0,045x–92,65	0,60	0,409	<0,0001	yes
January	y=0,019x–36,91	0,45	0,286	0,0006	yes
February	y=0,022x–43,00	0,46	0,304	0,0003	yes
March	y=0,024x–48,84	0,45	0,309	0,0002	yes
April	y=0,043x–87,97	0,39	0,230	0,0053	yes
May	y=0,068x–138,48	0,54	0,414	<0,0001	yes
June	y=0,083x–171,28	0,55	0,391	<0,0001	yes
July	y=0,100x–206,36	0,46	0,301	0,0003	yes
August	y=0,085x–177,37	0,49	0,330	<0,0001	yes
September	y=0,042x–91,31	0,29	0,185	0,0243	no
October	y=0,029x–62,42	0,31	0,210	0,0107	no
November	y=0,012x–26,25	0,22	0,133	0,1098	no
December	y=0,007x–13,89	0,22	0,124	0,1391	no

from the straight line. Given this, such a series can be classified as quasi-homogeneous.

At the same time, the beginning of the cooling phase cannot be clearly determined from the residual mass curve of the mean annual air temperature, as observations began when this phase was already underway. Similarly, it is impossible to determine the end of the warming phase, which continues to this day. Therefore, this observation series is not representative for the determination of sustainable mean value, namely the norm [Andreyanov, 1959]. An example of changing the mean value of observation series depending on the presence or absence of a representative period (phases of increase and decrease) is shown in paper Gorbachova L. [2015]. Note that since the observation series of the mean annual air temperature still has phases of cooling and warming, although they are incomplete, it can be attributed to quasi-stationary. That is why it is important for such a series to repeat the research periodically. In addition, there is the question of determining the climatic norm of air temperature, which is now according to the recommendations of the WMO [1990, 2018] is determined for a 30-year period that does not take into account long-term cyclical fluctuations.

Tendencies of mean monthly surface air temperature are similar to tendency to mean annual surface air temperature (Fig. 5). The differences are only for some months, namely for the period from September to December. For these months, the mass values of the mean monthly air temperature are close in appearance to a straight line, although they are also slightly deviate from it and even cross it (Fig. 5, *a*). This type of total curves is due to the presence of short full cycles of fluctuations, which are clearly traced in the cooling phase (Fig. 5, *b*).

Conclusion. For the period 1951—2020 on the Akademik Vernadsky station the observation series of the mean annual surface air temperature are quasi-homogeneous and quasi-stationary, as it has only a cooling phase and a warming phase of long-term cyclical fluctuations, which are also incomplete. According to the analysis of the residual mass curve, the transition from the cooling phase to the warming phase took place in 1982. This is in good agreement with the analysis of three statistical tests, which clearly indicate a disturbance of the homogeneity of observation series of the mean annual surface air temperature in 1982. This disturbance of homogeneity is due to the comparison of different phases of cyclical fluctuations (cooling and warming), which have different statistical characteristics.

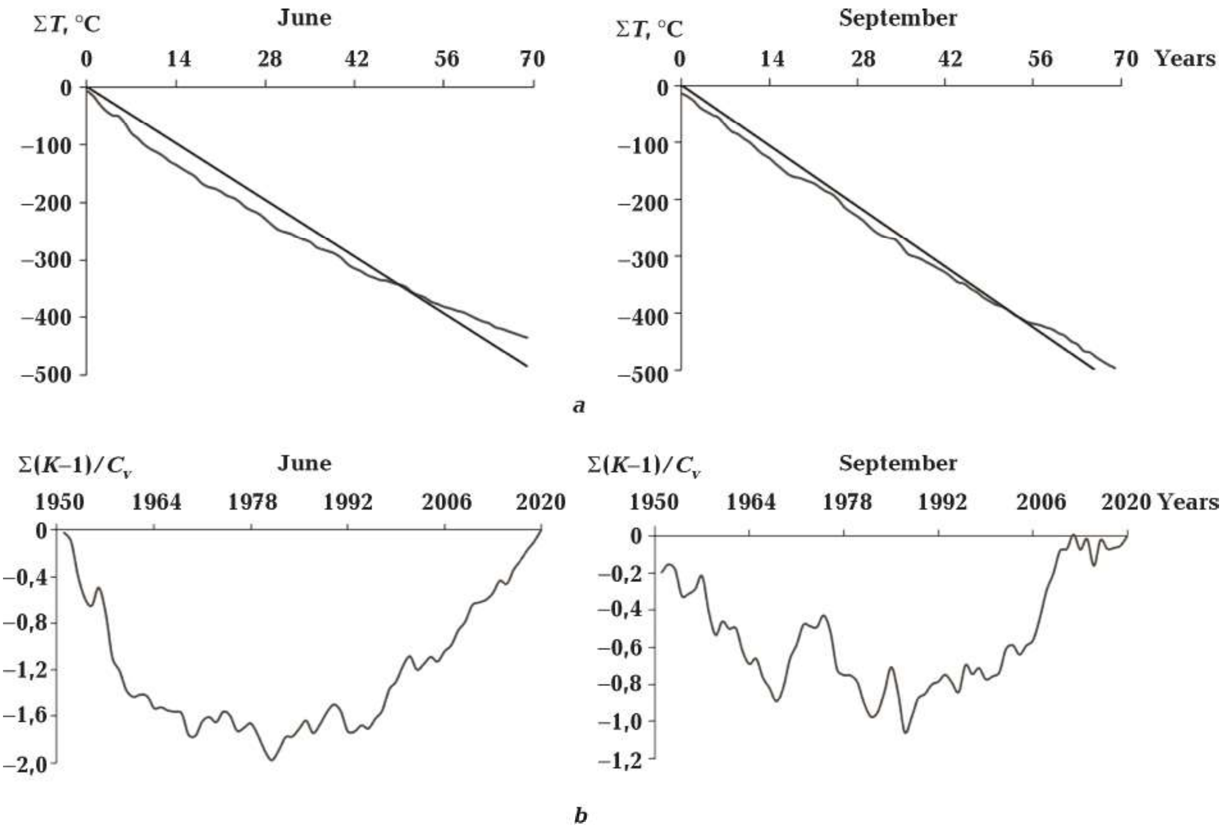

Fig. 5. Mass curves (*a*) and residual mass curve (*b*) of the mean monthly surface air temperature for individual months on the Akademik Vernadsky station, 1951—2020.

Tendencies of the mean monthly surface air temperature are similar to the tendency in mean annual temperature. The differences are only for some months, namely for the period from September to December. These months are characterized by the presence of short complete cycles of fluctuations, which are clearly visible in the cooling phase. This makes it difficult to determine the homogeneity of such series according to statistical tests.

The use of a complex analysis of surface air temperature with using statistical and graphical methods allows to obtain more thorough and reliable estimates of their homogeneity and stationarity. In addition, it is important to repeat the research periodically with increasing duration of observations.

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Оцінювання тенденцій, однорідності та стаціонарності температури повітря на Українській антарктичній станції «Академік Вернадський» протягом 1951—2020 рр.

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У цій праці представлено результати комплексного аналізу тенденцій приземної температури повітря на Українській антарктичній станції «Академік Вернадський». Антарктида є регіоном, у якому спостерігається висока швидкість підвищення приземної температури повітря. Особливо стрімкого потепління зазнав Антарктичний півострів, на якому спостерігається найбільше підвищення температури повітря у Південній півкулі. Отже, в Антарктиді дослідження зміни приземної температури повітря має важливе значення.

Українська антарктична станція «Академік Вернадський» розташована на острові Галіндез поблизу Антарктичного півострова. Дослідження приземної температури повітря є особливо актуальним саме для станції «Академік Вернадський», оскільки вона має складні умови формування. Мета досліджень — оцінювання тенденцій, однорідності та стаціонарності річних і середньомісячних значень приземної температури повітря на основі комбінованого підходу з використанням декількох статистичних та графічних методів на Українській антарктичній станції «Академік Вернадський». Використання різних статистичних методів, які різняться за характеристиками (чутливість до закону розподілу, автокореляційних зв'язків та ін.) дає змогу отримати достовірніші оцінки. Графічні методи надають можливість простежити тенденції з часом та ідентифікувати періоди змін, проаналізувати циклічні коливання та їхні характеристики (фази підвищення і зниження, їх тривалість, синхронність, синфазність). Отже, для дослідження використано 4 статистичні тести (стандартний нормальний тест Алєксандерссона, тест Буішанда, тест Петтітта, відношення фон Неймана) та 2 графічні методи (сумарна крива і інтегральна крива відхилень).

На Українській антарктичній станції «Академік Вернадський» ряд спостережень за середньою річною температурою повітря є квазіоднорідним і квазістаціонарним, оскільки він має тільки фазу похолодання і фазу потепління тривалих циклічних коливань, які є ще і незавершеними. Перехід від фази похолодання до фази потепління відбувся у 1982 р. Тенденції середніх місячних температур повітря подібні до тенденцій середньої річної температури. Відмінності є тільки для деяких місяців, а саме для періоду з вересня по грудень.

Ключові слова: температура повітря, циклічні коливання, стаціонарність, однорідність, Антарктида, статистичні тести, графічні методи.