Changes in extreme temperature indices at the Ukrainian Antarctic Akademik Vernadsky station, 1951-2020

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Abstract

In the late 20th century, warming on the Antarctic Peninsula was most pronounced compared to other parts of Antarctica. However, air temperature showed a significant variability, which has become especially evident in recent decades. Thus, the investigation of air temperature trends on the Antarctic Peninsula is important. This study examines the extreme air temperature at the Ukrainian Antarctic Akademik Vernadsky station, located on Galindez Island, Argentine Islands Archipelago, near the Antarctic Peninsula. For 1951 to 2020, based on the daily air temperature data, the temporal trends of extreme air temperature were analyzed, using 11 extreme temperature indices. Based on linear trend analysis and the Mann-Kendall trend test, the TXn, TNn, TN90p, and TN90p indices showed an upward trend, whereas theFD0, ID0, TN10p, TX10p, and DTR indices showed a downward trend. Among them, annually, FD0, ID0, and TN10p significantly decreased by –0.427 days, –0.452 days, and –0.465%, respectively, whereas TXn and TNn increased by 0.164°C and 0.201°C, respectively. The indices TXx and TNn showed no statistically significant trends. The average annual difference between TX and TN (index DTR) showed a nonsignificant decreasing trend at –0.029°C $year^{-1}$. Thus, for the period of 1951-2020, the Ukrainian Antarctic Akademik Vernadsky station was subjected to warming.

Key words

Antarctica, trend, climate change, extreme air temperature, extreme indices, RStudio Software.

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1. Introduction

Climate change affects all parts of the Earth. However, researchers are paying particular attention to the investigation of climate change in Antarctica, which is largely covered by glaciers. Antarctic ice sheets directly affect the global climate and ocean circulation (Kuhn et al. 2010), and an increase in the area and mass of the glacier ice contributes to lowering sea levels, intensifies atmospheric circulation, and increases planetary albedo (Lurcock, Florindo 2017; Silva et al. 2020). One of the most profound consequences of climate warming is the degradation of glacial sheets, including on the Antarctic peninsula (Vaughan, Doake 1996; Turner et al. 2002; Grischenko et al. 2005; Kuhn et al. 2010; Wouters et al. 2015; Silva et al. 2020; Diener et al. 2021). Warming on the Antarctic Peninsula has also impacts on the terrestrial flora, seasonal snow cover, lake ecology, penguin distribution, ice-shelf distribution, glacier thickness, and sea-ice duration (Vaughan et al. 2003; Turner et al. 2014, 2016).

The rate and tendencies of warming at the Antarctic Peninsula are still subject of debate (Vaughan et al. 2003; Martazinova et al. 2010; Stastna 2010; Qu et al. 2011; Schneider et al. 2012; Bromwich et al. 2013, Ding, Steig 2013; Franzke 2013; Tymofeyev 2013; Turner et al. 2016; Gonzalez, Fortuny 2018; Sato et al. 2021), and the peninsula presents physical and geographical features that distinguish it from the rest of Antarctica (King, Tuner 1997; Vaughan et al. 2003). The rugged alpine topography, a maritime climate along the west and central costa, and a continental climate along the east coast result in higher temperatures at the west coast compared to areas with similar latitudes and elevations on the east coast (Morris, Vaughan 1994). Several studies have reported stable trends in surface air temperature increase on the Antarctic Peninsula. For example, Vaughan et al. (2003) demonstrated that the Antarctic Peninsula has warmed at 3.7 ± 1.6°C century^{-1}, which is several times the rate of global warming and different to most of the other station records from the Antarctic continent. However, Bromwich et al. (2013) reported a linear increase in annual temperature between 1958 and 2010 by 2.4 ± 1.2°C, establishing central West Antarctica as one of the fastest-warming regions globally. Stastna (2010) reported about three distinct regions with different trends of warming on the Antarctic Peninsula. Franzke (2013) and Turner et al. (2014, 2016, 2020, 2021) reported extremely high rates of surface air temperature changes on the Antarctic Peninsula. Moreover, according to Turner et al. (2016), Gonzalez and Fortuny (2018), and Sato et al. (2021), on the Antarctic Peninsula, the surface air temperature varies significantly, which has been especially evident in recent decades. Thus, current research is aimed at understanding such variable trends and the factors that determine them (Clem et al. 2019; Bozkurt et al. 2020; Turner et al. 2020; Bozkurt et al. 2021).

This study examines the extreme air temperatures in the Ukrainian Antarctic Akademik Vernadsky station, located on the western side of the Antarctic Peninsula. Historical observations of this station have been used in various studies that investigated the trends of average and extreme temperatures. For example, Turner et al. (2005) reported that the Antarctic Peninsula has experienced a major warming over the last 50 years and that on the Akademik Vernadsky station, the surface air temperature increased at a rate of 0.56°C decade^{-1} over the year and 1.09°C decade^{-1} during the winter. Martazinova et al. (2010) reported that according to the data of the Akademik Vernadsky station, the increase in the mean annual air temperature exceeded 2°C for the observation period 1947-2007. According to Franzke (2013), the Akademik Vernadsky station has been experiencing a significant warming trend of about 0.6°C decade^{-1} over the last few decades. Tymofeyev (2013) reported the greatest warming, with a linear trend coefficient of 0.53°C/10 years, at the Akademik Vernadsky station. At the same time, modern warming is separated by a period of relative cooling in the beginning and middle 1970s. Turner et al. (2020) reported that 13 of the 17 stations have experienced a positive trend in annual mean temperature over the full length of their record (until 2018), with the largest being observed at the Akademik Vernadsky station (0.46 ± 0.15°C·decade^{-1}). One of the latest in-depth studies analyzing the formation conditions and trends of maximum and minimum air temperature in Antarctica is the paper Turner et al. (2021). However, both in this paper and in others, the climate extremes indices were not used. These indices have been developed by the expert team of the World Meteorological Organization (Zhang, Yang 2004; Tashebo et al. 2021) and contribute to a better understanding and analysis of the trends of climate change, particularly the temperature and rainfall variables (Brown et al. 2010; Costa et al. 2020; Zhou et al. 2020; Tashebo et al. 2021). In this context, the objective of this paper was to investigate the extreme temperature indices change at the Ukrainian Antarctic Akademik Vernadsky station for the period 1951-2020.

2. Study area, data, and methodology

2.1. Study area

Until 1996, the Ukrainian Antarctic Akademik Vernadsky station was a British Faraday station. The station is located on Galindez Island, Argentine Islands Archipelago, near the western coast of the Antarctic Peninsula (Fig. 1) in the middle part of the peninsula (65.25°S, 64.27°W). The island is dominated by large-scale circumpolar circulation in the atmosphere and ocean (King, Tuner 1997).

Fig. 1. Location of the Ukrainian Antarctik Akademik Vernadsky station (background graphic from Klok, Kornus 2021).

The climate of Galindez Island is marine subarctic (King, Tuner 1997; Franzke 2013). Wind and temperatures conditions are mainly formed by the mountain system of the Antarctic Peninsula (Turner et al. 2002; King, Comiso 2003). The average plateau height is 2,000 m above sea level and the height of individual peaks reaches 2,800 m (King, Tuner 1997). This system forms the foehn wind, and the air cools over the ice cover and forms local winds. The area over the Pacific Ocean is dominated by the low-pressure systems that move eastwards towards the Antarctic Peninsula (King, Comiso 2003), causing frequent precipitation and strong winds, with frequent snowfall and snowstorms. The anticyclonic type of weather is less common. In this case, calm frosty weather is established for a long period, sometimes with fog and frost (King, Tuner 1997; King, Comiso 2003).

For the period 1951-2020, the warmest month of the year was January, with a multi-annual mean monthly temperature of +0.8°C, and the coldest month was August, with a multi-annual mean monthly temperature of –8.7°C. The highest mean monthly air temperature was +2.4°C (February) and the lowest –20.1°C (July) (Table 1).

Table 1. Multiannual mean monthly air temperature (°C) at the Akademik Vernadsky station for the period of 1951-2020.

Temperature	Mean	Highest		Lowest	
		Value	Year	Value	Year
January	0.8	2.3	1985	–1.4	1959
February	0.7	2.4	2001	–3.0	1953
March	–0.4	1.6	2001	–4.6	1953
April	–2.4	0.5	2013	–13.9	1959
May	–4.2	–0.2	2001	–13.8	1959
June	–6.2	–1.1	1998	–17.1	1958
July	–8.4	–2.6	1989, 1998	–20.1	1959
August	–8.7	–2.9	2003	–17.4	1954
September	–7.1	–2.1	1970	–14.1	1987
October	–4.5	–0.6	2010	–9.5	1994
November	–2.1	0.1	1994	–4.7	1954
December	–0.2	1.7	2009	–1.7	1958

2.2. Data

In this study, daily air temperature data for eight terms (0, 3, 6, 9, 12, 15, 18, 21 UTC) of the Akademik Vernadsky station, provided by the National Antarctic Scientific Center of Ukraine (NASC), were used; the period was 1951-2020. Data before 1996 were kindly provided by the Meteorological Information Database of the British Antarctic Survey.

When carrying out investigations, the quality of the initial data is extremely important. During the existence of the Akademik Vernadsky station, various measuring instruments and complexes were used to measure surface air temperature. Thus, regular meteorological observations of surface air temperature with the help of mercury thermometers in a psychrometric booth were started in 1947. In 1985, the Synoptic and Climatological Automatic Weather Station (SCAWS) was installed in a psychrometric booth, which was replaced by the Modular Automatic Weather Station (MAWS) in 1992. In March 2011, the MAWS system was replaced by the Ukrainian-made Mobile Meteorological Complex "Troposphere" (Mobile AWS "Troposphere"). This complex contains the temperature sensor in its own radiation protection, with artificial ventilation. In April 2020, the Mobile AWS "Troposphere" was transferred to reserve status. The main data source currently is the automatic weather station Vaisala AWS-310, which was installed 1 year earlier. This station contains the temperature sensor in its own radiation protection, with passive ventilation.

In the period from 1947 to 1950, the measurement of surface air temperature took place at different times. However, the observation data were incomplete, and data were therefore checked for missing values, gross errors, and outliers that exceeded four standard deviations from the mean for each day. The missing values were recovered by multiple regression depending on air temperature before and after the missing value; such regression dependences were established for each month of the year. The amount of missing data was insignificant (0.1% of the total data), and there were no gross errors or significant outliers in our dataset. After quality control procedures, daily minimum and maximum air temperature were calculated.

2.3. Methodology

A core set of 27 indices has been developed by the Expert Team on Climate Change Detection and Indices (ETCCDI) to standardize the definitions and analysis of extremes (Peterson et al. 2001; Klein Tank et al. 2006). Of these 27 indices, only 16 refer to air temperature, and the remaining ones refer to precipitation. Based on the analysis of the temperature regime at the Akademik Vernadsky station during the recent 70 years, 11 extreme temperature indices were chosen (Table 2) as they are most suitable to study the temporal characteristics of extreme air temperature events. The annual indices and their trend equations were obtained using the RStudio Software (version 1.4.1717) (R Core Team 2017). Percentile indices were calculated using the standard reference period of 1981-2010 to facilitate comparison of the results with those of other studies using the same reference period. The Mann-Kendall non-parametric trend test was employed to assess the statistical significance of the indices series (Mann 1945; Kendall 1975), using the RStudio Software. The statistical significance of trends was estimated depending on the τ value:

$$\tau = \frac{P-Q}{n(n-1)/2}, \quad (1)$$

where P is the number of concordant pairs, Q is the number of discordant pairs, and n is the total amount of data.

Table 2. Definition of extreme air temperature indices.

Index	Name	Definition	Unit
FD0	Frost days	Annual count when TN (daily minimum) < 0°C	Days
ID0	Ice days	Annual count when TX (daily maximum) < 0°C	Days
TXx	Highest Tmax	Highest annual value of daily maximum temperature	°C
TNx	Highest Tmin	Highest annual value of daily minimum temperature	°C
TXn	Lowest Tmax	Lowest annual value of daily maximum temperature	°C
TNn	Lowest Tmin	Lowest annual value of daily minimum temperature	°C
TN10p	Cool nights	Percentage of days when TN < 10^{th} percentile	%
TX10p	Cool days	Percentage of days when TX < 10^{th} percentile	%
TN90p	Warm nights	Percentage of days when TN > 90^{th} percentile	%
TX90p	Warm days	Percentage of days when TX > 90^{th} percentile	%
DTR	Diurnal temperature range	Average annual difference between TX and TN	°C

3. Results

3.1. Cold extremes indices (ID0, FD0, TXn, TNn and TX10p, TN10p)

The number of frost days during the period of 1951-2020 varied from 149 to 254. The maximum number of frost days was observed in 1967 and 1969 (349 days) and the minimum number in 2001 (271 days). The ID0 and FD0 indices significantly decreased at –0.427 and –0.452 day $year^{-1}$, respectively (Table 3, Fig. 2).

Table 3. Annual trends of the extreme indices of daily air temperature for the Academik Vernadsky station, 1951–2020.

Temperature indices	Trend equation	R^2	τ	*p*-value	Statistical significance of trend
FD0	y = –0.46x + 1164	0.18	–0.281	0.0006	yes
ID0	y = –0.45x + 1096	0.15	–0.249	0.0024	yes
TXx	y = 0.016x – 23.8	0.06	0.174	0.0352	no
TNx	y = 0.007x – 10.0	0.03	0.137	0.0999	no
TXn	y = 0.16x – 347.4	0.24	0.338	<0.0001	yes
TNn	y = 0.20x – 425.2	0.32	0.369	<0.0001	yes
TN10p	y = –0.46x + 941.4	0.44	–0.420	<0.0001	yes
TX10p	y = –0.28x + 578.6	0.34	–0.407	<0.0001	yes
TN90p	y = 0.07x – 124.4	0.13	0.272	0.0010	yes
TX90p	y = 0.06x – 101.3	0.15	0.276	0.0008	yes
DTR	y = –0.029x + 62.3	0.47	–0.469	<0.0001	yes

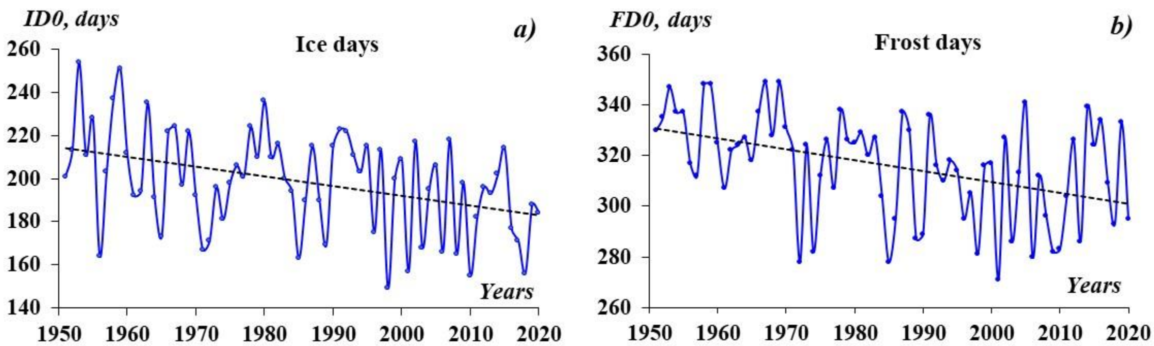

Fig. 2. Annual count when TX (daily maximum) < 0°C (a) and TN (daily minimum) < 0°C (b).

The indices TXn and TNn showed an upward trend. Annually, TXn and TNn increased by 0.164°C and 0.201°C, respectively (Table 3, Fig. 3). The lowest air temperature was observed in the winter period of 1958 (–42.4°C). In the winter of 1977, the air temperature also dropped below –40°C (–40.2°C). The warmest winter was that of 1989, when the temperature did not fall below –10.2°C at night and below –7.2°C during the day.

Annually, the TX10p and TN0p indices showed a significant decrease in cool days and cool nights by 0.46% and 0.28%, respectively (Table 3, Fig. 4). In 1959, the largest number of cold days and nights, namely 43.8% and 58.3%, respectively, was observed. In 1989, the number of cool days and nights was lowest.

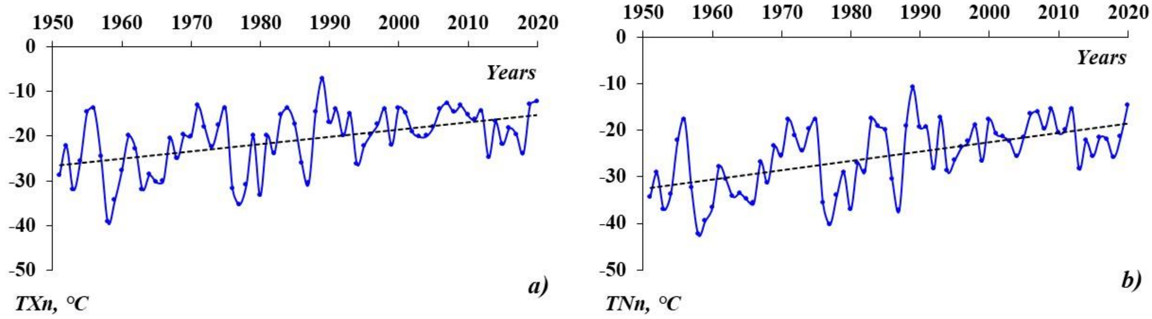

Fig. 3. Lowest annual values of daily maximum (a) and minimum (b) air temperatures.

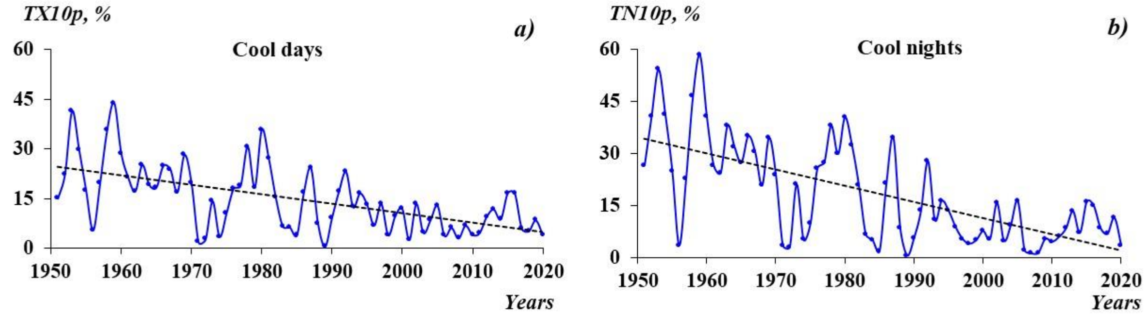

Fig. 4. Percentage of days when TX < 10^{th} (a) and TN < 10^{th} (b) percentile of 1981-2010.

3.2. Hot extremes indices (TXx, TNx, TX90p, and TN90p)

The TXx and TNx indices showed no statistically significant tendencies for the period of 1951-2020 (Table 3, Fig. 5). Annually, the TX90p and TN90p indices showed a small increase in warm days and nights by 0.056% and 0.067%, respectively (Table 3, Fig. 6). The highest air temperature was observed in the summer of 1985, with +10.9°C during the day and +5.1°C at night. In the summer of 1973, the daytime temperature did not exceed +4.8°C, and in the summer of 1978, the night air temperature dropped to +1.3°C. The largest number of warm days was observed in 2018 and that of warm nights in 1998, with 15.3% and 19.3%, respectively. In 2002, the number of warm days was lowest (4.2%), whereas the number of warm nights was lowest in 1958 and 1959 (2.7%).

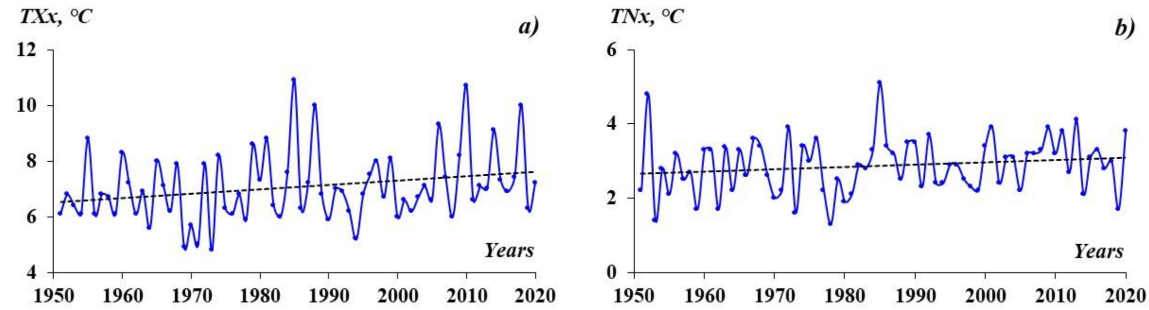

Fig. 5. Highest annual values of daily maximum (a) and minimum (b) air temperatures.

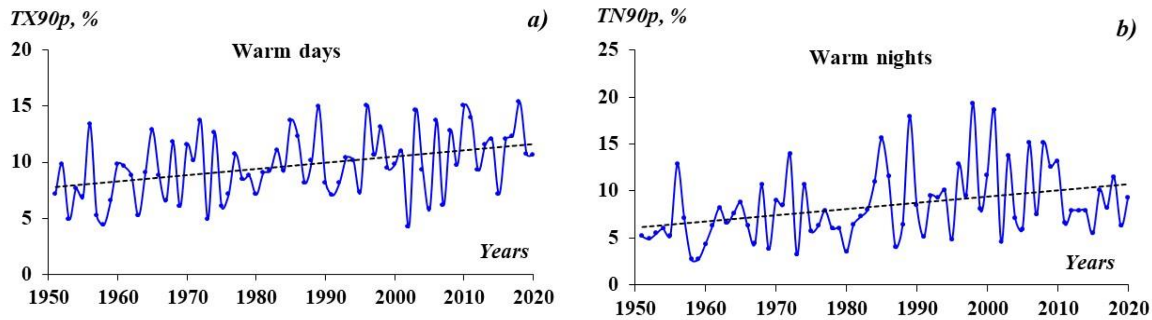

Fig. 6. Percentages of days when TX > 90th (a) and TN > 90th (b) percentile of 1981-2010.

DTR index is an average annual difference between daily maximum and minimum air temperature. DTR index shows a small negative trend (–0.026°C/year) over the last 70 years (Table 3, Fig. 7). This trend is due to larger increases in average annual minimum air temperatures (0.06°C/year) than average annual maximum air temperatures (0.03°C/year) over the same period.

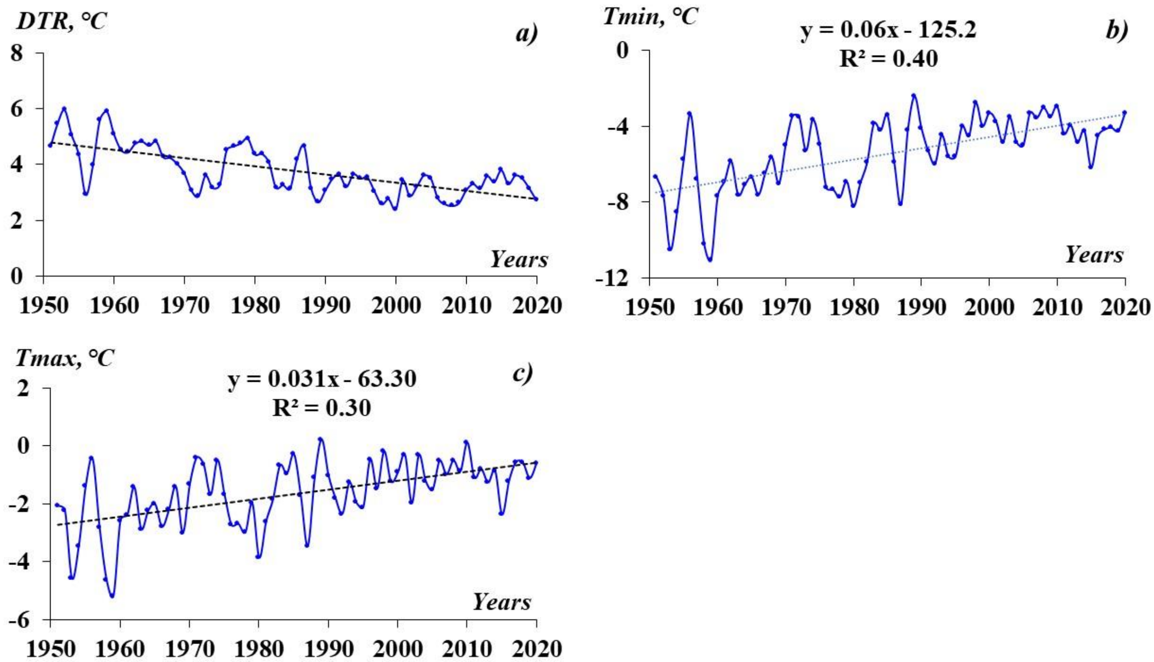

Fig. 7. Average annual difference between TX and TN (a), average annual minimum (b) and maximum (c) air temperatures.

4. Discussion

Analysis of 11 extreme air temperature indices at the Ukrainian Antarctic Akademik Vernadsky station showed the indicate unequivocal signs of heating. These results are in good agreement with those of studies using other methodological approaches (Turner et al. 2005, 2014, 2020, 2021; Franzke 2013; Gonzalez, Fortuny 2018; Bozkurt et al. 2021). Turner et al. (2005) reported the positive statistically significant trend of the mean annual air temperature at the Akademik Vernadsky station, whereas Franzke (2013) reported that for the period of February 1947 to January 2011, the Akademik Vernadsky station experienced a significant warming trend and the magnitude of extremely cold temperatures was reduced; however, the annual maximum temperature did not increase. Some authors, such as Turner et al. (2016) and Gonzalez and Fortuny (2018), reported the decrease tendencies of the annual mean temperature on the Antarctic Peninsula in recent decades, including at the Vernadsky station. This was explained by the natural internal variability of the regional atmospheric circulation. Investigation of surface air temperature trends using the latest observational data demonstrated the presence of a persistent warming trend (Turner et al. 2020, 2021; Bozkurt et al. 2021), which is also confirmed by our research. Turner et al. (2021) researched the variability and change in the frequency of extreme daily mean temperatures in Antarctica; for the Akademik Vernadsky station, the authors observed an increase in the percentage of extreme warm days and a decrease in cold days. On the Antarctic Peninsula, the warming trend will continue in the future. According to the global climate models, forecasts suggest that the Antarctic Peninsula temperatures will increase more significantly than in other parts of Antarctica and in the world (Chyhareva et al. 2019; Stiegert et al. 2019). Chyhareva et al. (2019) reported that for the Antarctic Peninsula region for RCP4.5 and RCP8.5 scenarios on average forecast to reduce the cold period; for the Akademik Vernadsky station, this process will be three times more intensive, indicating that the region is more vulnerable to climate change. Stiegert et al. (2019) reported that with a temperature increase by 1.5°C, irreversible and dramatic changes to glacial, terrestrial, ocean, and biological systems on the Antarctic Peninsula can be expected.

5. Conclusions

Our study presents an evaluation of climate extremes indices by focusing on the analysis of daily minimum and maximum air temperatures at the Ukrainian Antarctic Akademik Vernadsky station. The results show a trend of warming for the period of 1951-2020. This is indicated by the calculated extreme air temperature indices, which showed statistically significant tendencies, namely during the recent 70 years:

- indices of ice and frost days, cool nights and days, and the diurnal temperature range significantly decreased;
- indices of warm nights and days, lowest annual values of daily maximum and minimum air temperature significantly increased.

In this study, the application of the climate indices made it possible to obtain more complete information about the tendencies of the extreme air temperature at the Ukrainian Antarctic Akademik Vernadsky station. Such results are highly important in the context of understanding the temporal variability of annual and seasonal air temperature on the Antarctic Peninsula. In general, the results of this investigation support previous findings. Further research should focus on the application of the climate indices for the investigation of the extreme temperature changes at the Akademik Vernadsky station during particular months or seasons.

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References

Bozkurt D., Bromwich D.H., Carrasco J., Hines K.M., Maureira J.C., Rondanelli R., 2020, Recent near-surface temperature trends in the Antarctic Peninsula from observed, reanalysis and regional climate model data, Advances in Atmospheric Sciences, 37, 477-493, DOI: 10.1007/s00376-020-9183-x.

Bozkurt D., Bromwich D.H., Carrasco J., Rondanelli R., 2021, Temperature and precipitation projections for the Antarctic Peninsula over the next two decades: contrasting global and regional climate model simulations, Climate Dynamics, 56, 3853-3874, DOI: 10.1007/s00382-021-05667-2.

Bromwich D.H., Nicolas J.P., Monaghan A.J., Lazzara M.A., Keller L.M., Weidner G.A., Wilson A.B., 2013, Central West Antarctica among the most rapidly warming regions on Earth, Nature Geoscience, 6, 139-145, DOI: 10.1038/NGEO1671.

Brown P.J., Bradley R.S., Keimig F.T., 2010, Changes in Extreme Climate Indices for the Northeastern United States, 1870-2005, Journal of Climate, 23 (24), 6555-6572, DOI: 10.1175/2010JCLI3363.1.

Chyhareva A., Krakovska S., Pishniak D., 2019, Climate projections over the Antarctic Peninsula region to the end of the 21st century. Part 1: Cold temperature indices, Ukrainian Antarctic Journal, 1 (18), 47-63. DOI: 10.33275/1727-7485.1(18).2019.131.

Clem K.R., Lintner B.R., Broccoli A.J., Miller J.R., 2019, Role of the South Pacific convergence zone in West Antarctic decadal climate variability, Geophysical Research Letters, 46 (12), 6900-6909, DOI: 10.1029/2019GL082108.

Costa R.L., Baptista G.M.M., Gomes H.B., Silva F.D.S., da Rocha Júnior R.L., Salvador M.A., Herdies D.L., 2020, Analysis of climate extremes indices over northeast Brazil from 1961 to 2014, Weather and Climate Extremes, 28, DOI: 10.1016/j.wace.2020.100254.

Diener T., Sasgen I., Agosta C., Fürst J.J., Braun M.H., Konrad H., Fettweis X., 2021, Acceleration of dynamic ice loss in Antarctica from satellite gravimetry, Frontiers in Earth Science, 9, DOI: 10.3389/feart.2021.741789.

Ding Q., Steig E.J., 2013, Temperature change on the Antarctic Peninsula linked to the Tropical Pacific, Journal of Climate, 26 (19), 7570-7585, DOI: 10.1175/JCLI-D-12-00729.1.

Franzke C., 2013, Significant reduction of cold temperature extremes at Faraday/Vernadsky station in the Antarctic Peninsula, International Journal of Climatology, 33 (5), 1070-1078, DOI: 10.1002/joc.3490.

Gonzalez S., Fortuny D., 2018, How robust are the temperature trends on the Antarctic Peninsula, Antarctic Science, 30 (5), 322-328, DOI: 10.1017/S0954102018000251.

Grischenko V.F., Timofeyev V.E., Klock S.V., 2005, Impacts of components of glaciosphere to climate change at the Antarctic Peninsula region, (in Ukrainian), Ukrainian Antarctic Journal, 3, 99-107, DOI: 10.33275/1727-7485.3.2005.574.

Kendall M.G., 1975, Rank Correlation Methods, 4th edition, Charles Griffin, London, 202 pp.

King J.C., Comiso J.C., 2003, The spatial coherence of interannual temperature variations in the Antarctic Peninsula, Geophysical Research Letters, 30 (2), DOI: 10.1029/2002GL015580.

King J.C., Turner J., 1997, Antarctic meteorology and climatology, Cambridge University Press, DOI: 10.1017/CBO9780511524967,

Klein Tank A.M.G., Peterson T.C., Quadir D.A., Dorji S., Zou X., Tang H., Santhosh K., Joshi U.R., Jaswal A.K., Kolli R.K., Sikder A.B., Deshpande N.R., Revadekar J.V., Yeleuova K., Vandasheva S., Faleyeva M., Gomboluudev P., Budhathoki K.P., Hussain A., Afzaal M., Chandrapala L., Anvar H., Amanmurad D., Asanova V.S., Jones P.D., New M.G., Spektorman T., 2006, Changes in daily temperature and precipitation extremes in central and south Asia, Journal of Geophysical Research, 111 (D16), DOI: 10.1029/2005JD006316.

Klok S.V., Kornus A.O., 2021, Intra-annual and long-periodic components in the changes of precipitation over the Antarctic Peninsula and their possible causes, Journal of Geology, Geography and Geoecology, 30 (3), 490-490, DOI: 10.15421/112144.

Kuhn M., Featherstone W., Makarynskyy O., Keller W., 2010, Deglaciation-induced spatially variable sea level change: a simple-model case study for the Greenland and Antarctic ice sheets, The International Journal of Ocean and Climate Systems, 1 (2), 67-84, DOI: 10.1260/1759-3131.1.2.67.

Lurcock P., Florindo F., 2017, Antarctic Climate History and Global Climate Changes, Oxford University Press, DOI: 10.1093/oxfordhb/9780190699420.013.18.

Mann H.B., 1945, Nonparametric tests against trend, Econometrica, 13 (3), 245-259, DOI: 10.2307/1907187.

Martazinova V.F., Tymofeyev V.E., Ivanova Y.K., 2010, Current regional climate of the Antarctic Peninsula and Akademik Vernadsky Station, (in Russian), Ukrainian Antarctic Journal, 9, 231-248. DOI: 10.33275/1727-7485.9.2010.411.

Morris E.M., Vaughan D.G., 1994, Snow surface temperatures in West Antarctica, Antarctic Science, 6 (4), 529-535, DOI: 10.1017/S0954102094000787.

Peterson T.C., Folland C., Gruza G., Hogg W., Mokssit A., Plummer N., 2001, Report on the Activities of the Working Group on Climate Change Detection and Related Rapporteurs 1998-2001, WMO, Rep. WCDMP-47, WMO-TD 1071, Geneve, Switzerland, available online http://etccdi.pacificclimate.org/docs/wgccd.2001.pdf (data access 13.06.2022).

Qu X., Hall A., Boe J., 2011, Why does the Antarctic Peninsula warm in climate simulations?, Climate Dynamics, 38 (5-6), 913-927, DOI: 10.1007/s00382-011-1092-3.

R Core Team, 2017, R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria, https://www.r-project.org/.https://www.r-project.org/.

Sato K., Inoue J., Simmonds I., Rudeva I., 2021, Antarctic Peninsula warm winters influenced by Tasman Sea temperatures, Nature Communications, 12, DOI: 10.1038/s41467-021-21773-5.

Schneider D.P., Deser C., Okumura Y., 2012, An assessment and interpretation of the observed warming of West Antarctica in the austral spring, Climate Dynamics, 38, 323-347, DOI: 10.1007/s00382-010-0985-x.

Silva A.B., Arigony-Neto J., Braun M.H., Espinoza J.M.A., Costi J., Jaña R., 2020, Spatial and temporal analysis of changes in the glaciers of the Antarctic Peninsula, Global and Planetary Change, 184, DOI: 10.1016/j.gloplacha.2019.103079.

Stastna V., 2010, Spatio-temporal changes in surface air temperature in the region of the northern Antarctic Peninsula and south Shetland islands during 1950-2003, Polar Science, 4 (1), 18-33, DOI: 10.1016/j.polar.2010.02.001.

Stiegert M., Atkinson A., Banwell A., Brandon M., Convey P., Davies B., Downie R., Edwards T., Hubbard B., Marshall G., Rogelj J., Rumble J., Stroeve J., Vaughan D., 2019, The Antarctic Peninsula under a 1.5°C global warming scenario, Frontiers in Environmental Science, 7, DOI: 10.3389/fenvs.2019.00102.

Tashebo G.B., Mekonn E.F., Eshete A.A., 2021, Trends in daily temperature and precipitation extremes over Dire-Dawa, 1980-2018, Journal of Environment and Earth Science, 11 (9), 31-37, DOI: 10.7176/JEES/11-9-03.

Turner J., Barrand N.E., Bracegirdle T.J., Convey P., Hodgson D.A., Jarvis M., Jenkins A., Marshall G., Meredith M.P., Roscoe H., Shanklin J., French J., Goosse H., Guglielmin M., Gutt J., Jacobs S., Kennicutt II M.C., Masson-Delmotte V., Mayewski P., Navarro F., Robinson S., Scambos T., Sparrow M., Summerhayes C., Speer K., Klepikov A., 2014, Antarctic climate change and the environment: an update, Polar Record, 50 (3), 237-259. DOI: 10.1017/S0032247413000296.

Turner J., Colwell S.R., Marshall G.J., Lachlan-Cope T.A., Carleton A.M., Jones P.D., Lagun V., Reid P.A., Lagovkina S., 2005, Antarctic climate change during the last 50 years, International Journal of Climatology, 25 (8), 1147-1148, DOI: 10.1002/joc.1130.

Turner J., Lachlan-Cope T.A., Marshall G.J., Morris E.M., Mulvaney R., Winter W., 2002, Spatial variability of Antarctic Peninsula net surface mass balance, Journal of Geophysical Research, 107 (D13), DOI: 10.1029/2001JD000755.

Turner J., Lu H., King J., Marshall G.J., Phillips T., Bannister D., Colwell S., 2021, Extreme temperatures in the Antarctic, Journal of Climate, 34 (7), 2653-2668, DOI: 10.1175/JCLI-D-20-0538.1.

Turner J., Lu H., White I., King J.C., Phillips T., Hosking J.S., Bracegirdle T.J., Marshall G.J., Mulvaney R., Deb P., 2016, Absence of 21st century warming on Antarctic Peninsula consistent with natural variability, Nature, 535, 411-415, DOI: 10.1038/nature18645.

Turner J., Marshall G.J., Clem K., Colwell S., Phillips T., Lu H., 2020, Antarctic temperature variability and change from station data, International Journal of Climatology, 40 (6), 2986-3007, DOI: 10.1002/joc.6378.

Tymofeyev V.E., 2013, Multi-years' changes in the air temperature at the Antarctic Peninsula and the possible reasons, (in Ukrainian), Proceedings of Ukrainian Hydrometeorological Institute, 264, 9-17.

Vaughan D., Marshall G.J., Connolley W.M., Parkinson C., Mulvaney R., Hodgson D.A., King J.C., Pudsey C.J., Turner J., 2003, Recent rapid regional climate warming on the Antarctic Peninsula, Climatic Change, 60, 243-274, DOI: 10.1023/A:1026021217991.

Vaughan D.G., Doake C.S.M., 1996, Recent atmospheric warming and retreat of ice shelves of the Antarctic Peninsula, Nature, 379, 328-331, DOI: 10.1038/379328a0.

Wouters B., Martin-Español A., Helm V., Flament T., Van Wessem J.M., Ligtenberg S.R.M., Van Den Broeke M.R., Bamber J.L., 2015, Dynamic thinning of glaciers on the Southern Antarctic Peninsula, Science, 348 (6237), 899-903, DOI: 10.1126/science.aaa5727.

Zhang X., Yang F., 2004, RClimDex (1.0) User Manual, Climate Research Branch, Environment Canada, Ontario, available online https://acmad.net/rcc/procedure/RClimDexUserManual.pdf (data access 13.06.2022).

Zhou J., Huang J., Zhao X., Lei L., Shi W., Wang L., Wei W., Liu C., Zhu G., Yang X., 2020, Changes of extreme temperature and its influencing factors in Shiyang River Basin, Northwest China, Atmosphere, 11 (11), DOI: 10.3390/atmos11111171.