© Romanov P. Yu., Romanova N. A., 2023, Journal of Oceanological Research, 2023, Vol. 51, No. 3, P. 84–105

УДК 551.524.33 DOI: 10.29006/1564-2291.JOR-2023.51(3).4

RECENT TRENDS IN NEAR-SURFACE AIR TEMPERATURE IN ANTARCTICA FROM REANALYSYS AND STATION DATA

P. Yu. Romanov[1], N. A. Romanova[2]

[1]CREST Institute, City University of New York,
160 Convent Ave, New York, NY 10031, USA,
e-mail: peter.romanov@noaa.gov;
[2]Shirshov Institute of Oceanology, Russian Academy of Sciences,
36, Nakhimovskiy prospekt, Moscow, 117997, Russia,
e-mail: romanova@ocean.ru

This study utilizes monthly-mean records of near-surface air temperature from ground-based stations in Antarctica spanning the time period of 1980 to 2022 to estimate temperature trends in the region. Analysis of in situ data confirms the prevailing warming tendencies over the continent, with positive trends observed at 11 out of the 18 examined stations. Annual mean temperature trends reach 0.40 °C/decade, with the most significant warming observed in the Antarctic Peninsula, West Antarctica, and Inner Antarctica. Relatively weaker and mixed temperature trends occurred in the coastal areas of East Antarctica. Throughout the year, the spring season exhibited the most consistent upward trends across the continent. Comparing current temperature trends with earlier estimates has revealed increased warming at most Antarctic stations in recent years. Four widely used reanalysis datasets – ERA5, JRA55, MERRA2, and CFSR – were examined to evaluate their ability to reproduce the observed temperature trends in situ. Among these four datasets temperature trends inferred from ERA5 provided the best fit to the station data. However, even in ERA5, the uncertainty in trend estimates was comparable to the magnitude of trend variation between stations. This suggests a limited ability of available reanalysis datasets to accurately reproduce the spatial distribution and patterns of temperature trends across the continent.

Keywords: Antarctic region, near-surface air temperature, station records, reanalysis datasets, temperature trends

Introduction

Climate variability and trends in the high-latitude region of the Southern Hemisphere are the subjects of extensive discussion within the climatological, atmospheric, and oceanographical research communities. Due to its high albedo and consistently low temperatures, this region plays a critical role in the Earth's climate system. Its influence on weather and climate processes extends to the lower latitudes of the Southern Hemisphere and even across the equator. (Weller, 1998; Ho et al., 2005). Changing climate in Antarctica is manifested through a range of observable phenomena. Examples include the deepening of the circumpolar trough (Romanov, Romanova, 2021), the associated increase of cyclone activity in the region (Yu et al., 2010), and the intensification of circumpolar westerlies around Antarctica (Romanova, Romanov, 2019). The observed changes also include increased snowfall (Marshall et al., 2017; Medley et al., 2019), glacier retreat (Cook et al., 2016, Bradley et al., 2023), increase of subsurface ocean temperature and heat content (Gille, 2008), changes in the ocean salinity, ice concentration and ice extent (Hobbs et al., 2016; Menezes et al., 2017; Mokhov and Parenova, 2021). These changes have profound implications for both terrestrial and marine ecosystems (e. g., Smith et al., 2017; Kennicutt et al., 2015; Amesbury et al., 2017).

Still, among various environmental parameters in Antarctica, most attention is attracted to its thermal regime and variability. To a large extent this attention is explained by pronounced warming trends, which have been observed over the continent in the past several decades. Particularly robust upward trends of over 0.5 °C/decade observed over the Antarctic Peninsula (e. g., Carrasco, 2013) have established it as one of the fastest warming regions on Earth. Similar, albeit slightly less pronounced, discernible upward tendencies in near-surface air temperature have been documented at various locations within the inner continent, including the South Pole and West Antarctica (Clem et al., 2020; Bromwich et al., 2013). The warming of the Antarctic climate has led to changes in other integral components and features of the Antarctic environment. These include the sea ice variability, glacier and ice shelf dynmaics, vegetation cover properties, ocean productivity, permafrost state (Bintanja et al., 2013; Guglielmin et al., 2014; Pinkerton et al., 2021; Eayrs et al., 2021; Cannone et al., 2022). Recent record-hot summer weather events in the Antarctic Peninsula along with an exceptional drop in the Antarctic sea ice extent in 2022 and 2023 (Raphael and Handcock, 2022; WMO, 2023) have further boosted interest in Antarctic climate change and stimulated speculation regarding the potential acceleration of warming processes in the region (Cannone et al., 2022; Bradley et al., 2023).

Characterizing temperature trends in Antarctica is complicated by their strong seasonal variability (Nicolas and Bromwich, 2011). Long-term temperature changes in Antarctica are also spatially heterogeneous: Rather than warming, cooling trends of –0.2 to –0.3 °C/decade in the annual mean temperature have been observed in the coastal regions of East Antarctica (e. g., Turner et al., 2019; Zhu et al., 2021). Besides long-term, multidecadal, changes, Antarctic temperatures demonstrate strong year-to year variations and experience changes on intermediate, decadal time scales. In particular, as observed by Turner et al. (2016) warming of the Antarctic Peninsula since the end of 1970s have slowed down and even turned to cooling during the period 1999–2014. Therefore, trend estimates are strongly dependent on the specific time interval chosen for analysis (Gonzalez and Fortuny, 2018) and may change with each new record added to the time series. As a result, frequent reassessment of the trends with the most recent temperature observations is crucial to ensure current and accurate estimates.

Ground-based observations present a reliable and consistent source of data to explore temperature variations in Antarctica. With some stations operating since the late 1950s, ground-based data have been extensively used to assess long-term temperature changes and trends (e. g., Turner et al., 2019; Bozkurt et al., 2020). The network of ground stations, however, is sparse: continuous and sufficiently long temperature records suitable for climate studies are available from fewer than 20 stations with most of these stations located in the coastal zone of Antarctica. Due to limited spatial coverage, it is not possible to obtain spatially detailed estimates of continental-scale temperature changes and trends using in situ observations. Although the number of automated ground-based stations has grown rapidly particularly since the early 2000s (Jones & Lister, 2015), additional time is still needed for these records to reach a length sufficient for climatological applications.

Atmospheric reanalysis datasets help to close the gap in the area coverage by offering spatially continuous air temperature estimates throughout the entire Antarctic region. These datasets have also been used extensively to infer and assess temperature trends in Antarctica (e. g., Huai et al., 2019; Yu et al., 2010). However, available estimates vary substantially across different reanalysis schemes, indicating considerable uncertainties associated with them. Limited efforts have been made thus far to quantitatively compare different reanalysis datasets to in situ instrumental measurements in the Antarctic region and assess the validity and accuracy of model-based trends. Previous research in this area predominantly involved earlier generation reanalysis datasets (NCEP1, NCEP-DOE, MERRA, ERA-Interim) and utilized temperature records with end dates ranging from several years to over a decade ago (e. g., Wang et al., 2016; Yang et al., 2022).

In this study we use records of the near-surface air temperature at Antarctic weather stations spanning from 1980 to 2022. The primary objective was to evaluate temperature changes in Antarctica over the last 43 years and to create the most up-to date estimates of the temperature trends at the station location. Additionally, the study aims to assess the accuracy and consistency of reanalysis-derived temperature trends in Antarctica by comparing them with in situ data. This comparative analysis helps assess the ability of reanalysis datasets to provide a comprehensive characterization of air temperature trends across the continent.

Data and Methodology

In this work monthly-mean near-surface temperature data at Antarctic weather stations were acquired from the Reference Antarctic Data for Environmental Research (READER) dataset (http://www.antarctica.ac.uk/met/READER/) of the British Antarctic Survey. Among the 30 Antarctic stations represented in the READER dataset we selected 18 stations where records of the monthly mean surface air temperature were complete or near-complete (see Table 1). For the purposes of this study, we defined “near-complete” time series as those with gaps in the monthly air temperature records in less than 6 years or approximately 15 % of the total years since 1980.

All but three stations incorporated in the analysis are located in the Antarctic coastal region. Five of these coastal stations belong to the Antarctic Peninsula and nine stations are in the coastal area of East Antarctica. Two stations in East Antarctica, namely Amundsen Scott and Vostok, are categorized as Inner Antarctica to distinguish them from the coastal locations in East Antarctica. One station, McMurdo, represents the coastal area of West Antarctica. Another station, Macquarie, is situated on the eponymous subantarctic island in the Pacific sector of the Southern Ocean (see Figure 1).

Table 1 – Antarctic stations used in the study

No.	Station Name	Latitude	Longitude	Elevation, m	Region[1]	Full years of data records
1	Bellingshausen	66.2° S	58.9° W	16	AP	42
2	Esperanza	63.4° S	57.0° W	13	AP	41
3	Marambio	64.2° S	56.7° W	198	AP	39
4	Faraday (Vernadsky)	65.4° S	64.4° W	11	AP	42
5	Rothera	67.5° S	68.1° W	32	AP	41
6	Halley	75.5° S	26.4° W	30	AS-EA	40
7	Neumayer	70.7° S	8.4° W	50	AS-EA	39
8	Novolazarevskaya	70.8° S	11.8° E	119	AS-EA	41
9	Syowa	69.0° S	39.6° E	21	IS-EA	42
10	Mawson	67.6° S	62.9° E	16	IS-EA	40
11	Davis	68.6° S	78.0° E	13	IS-EA	41
12	Mirny	66.5° S	93.0° E	30	IS-EA	39
13	Casey	66.3° S	110.5° E	42	IS-EA	41
14	Dumont Durville	66.7° S	140.0° E	43	IS-EA	36
15	Vostok	78.5° S	106.9° E	3490	IA-EA	36
16	Amundsen Scott	90.0° S	0.0° W	2835	IA-EA	40
17	McMurdo	77.9° S	166.7° E	16	PS-WA	37
18	Macquarie	54.5° S	158.9° E	8	PS-WA	38

[1] Region codes are as follows: AP – Antarctic Peninsula, IS – Indian Ocean Sector of Antarctica, AS – Atlantic Ocean Sector of Antarctica, PS – Pacific Ocean Sector, IA – Inner Antarctica, EA – East Antarctica, WA – West Antarctica.

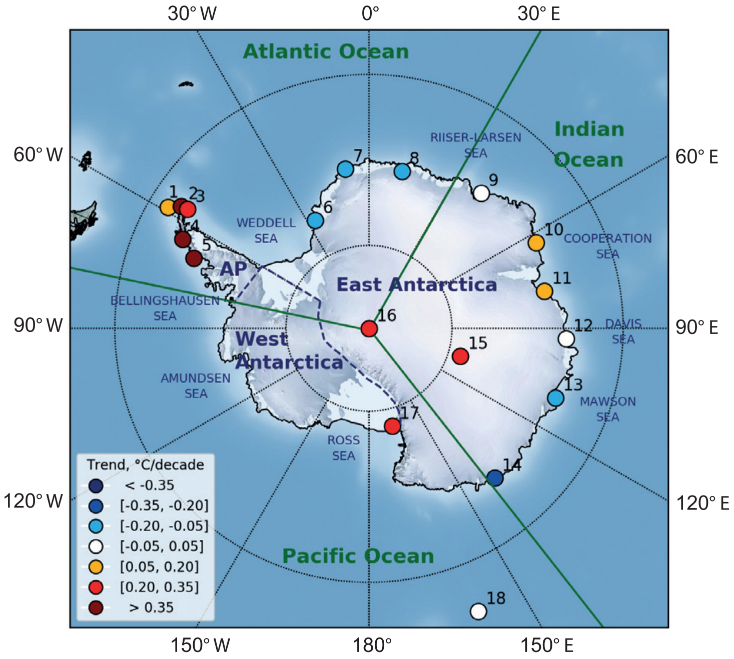

Fig. 1 – Location of Antarctic weather stations used in the study. Station names and auxiliary information on the stations is provided in Table 1. Dashed line shows the boundaries between the Antarctic subregions, East Antarctica, West Antarctica and Antarctic Peninsula (AP). Green lines identify the Atlantic, Indian and Pacific sector of the Southern Ocean. The color of the station markers represents the trend in the annual mean temperature in 1980–2022 inferred from in situ data in °C/decade

The following global reanalysis datasets have been included in the study, the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (hereafter, CFSR), the fifth generation atmospheric reanalysis of European Centre for Medium-Range Weather Forecasts, ECMWF (ERA5), the Japanese 55-year reanalysis created by the Japan Meteorological Agency, JMA (JRA55) and NASA's Second Modern Era Retrospective-Analysis for Research and Application (MERRA2). Table 2 provides a summary of the key characteristics of these datasets.

Table 2 – Characteristics of global atmospheric reanalysis datasets used in the study

Reanalysis	**Source**	**Citation**	**Period**	**Assimilation system**	**Horizontal grid**
ERA5	ECMWF	Hersbach et al. (2018)	1979-present	4DVAR	0.25°×0.25°
JRA55	JMA	Kobayashi et al. (2015)	1958-current	4DVAR	1.25°×1.25°
MERRA2	NASA	Gelaro et al. (2017)	1980-current	3DVAR	0.5°×0.625°
CFSR	NOAA	Saha et al. (2010)	1979-current	3DVAR	0.5°×0.5°

ERA5 is the latest global climate reanalysis scheme developed at ECMWF. It uses the ECMWF Integrated Forecast Model (IFS) with the data assimilation based on the four-dimensional variational analysis, 4DVAR (Hersbach et al., 2018). At 0.25° by 0.25° global grid cell size, ERA5 products provide the highest spatial resolution among all four reanalysis datasets included in this study. JRA55 (Kobayashi et al., 2015) is the second reanalysis of the Japan Meteorological Agency. It is based on an improved version of the JMA 4DVAR data assimilation and prediction system. The spatial resolution of JRA55 global gridded output is 1.25°×1.25° while the products are available back to 1958. A 3DVAR approach comprises the core of the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5) used in the NASA's MERRA2 reanalysis (Gelaro et al., 2017). The gridded dataset of MERRA2 variables is available at the spatial resolution of 0.5° latitude × 0.625° longitude. It is continuously updated and covers the time period from 1980 to the present. The NCEP CFSR (Saha et al., 2010) is a third-generation reanalysis product delivered at 0.5° spatial resolution. The CFSR reanalysis dataset covers the time period from 1979 to 2011 while later products generated within the same framework are available from NCEP's operational Climate Forecast System model version 2, CFSv2 (Saha et al., 2014). As pointed out in Saha et al. (2010) the atmospheric analysis system of CFSR as well as the scope of input data for the atmosphere are similar to the ones incorporated in MERRA2.

Monthly mean air temperature data from ground stations and from reanalysis datasets were used to calculate the corresponding season and annual mean values. Seasonal and annual means for in situ observations were calculated for years featuring complete monthly records for all three months of the season and all twelve months of the year, respectively. Trends in air temperature were estimated using a linear regression technique based on the least squares method. The p-value of less than 0.05 ($p < 0.05$) was used as a criterion when testing the trend for statistical significance. Other statistical data analysis techniques included Pearson correlation and the root-mean-square deviation (RMSD). To match and compare reanalysis and in situ temperature records, reanalysis products were interpolated to the location of each station using a bilinear interpolation technique.

Results

Time series of near-surface air temperature inferred from in situ data and four reanalysis datasets at Antarctic stations' locations have been examined to assess temperature variations and trends in annual, seasonal and monthly mean values. Analysis of these records revealed differences between the datasets in absolute temperature values but fairly close agreement on their interannual changes over the last 43 years. This is particularly evident in Figure 2, which presents several examples of the annual mean temperature time series inferred from in situ measurements and reanalysis datasets. The graphs are provided for stations located in different regions of the Antarctic continent, including the Antarctic Peninsula (Rothera), the Atlantic Ocean sector, the west of the Indian Ocean sector of Antarctica (Novolazarevskaya and Dumont-Durvile, respectively) and the inner region of East Antarctica (Vostok).

As seen from the plots in Figure 2, the reanalysis-based temperatures in the same location differ by mostly 5–8 °C. Considerable differences between matched in situ and reanalysis temperatures of up to 10 °C were also found by Zhu et al. (2021). At coastal locations, temperatures predicted by reanalysis models are generally lower than those observed in situ. The latter finding is consistent with earlier reports of the "cold bias" in model-based temperature estimates in the Antarctic coastal area (e. g., Zhang et al., 2022).

The observed spread in the estimated temperature values may be attributed to differences in the physical models and parameterizations incorporated in reanalysis schemes, as well as to different static and dynamic inputs used (e. g. Carter et al., 2022). Disagreement between in situ and reanalysis temperature may also be partially due to the different spatial resolution of the reanalysis datasets and the finite accuracy of bilinear interpolation, which was applied to project the gridded reanalysis data to the station location. To assess the effect of this latter factor, we tested two other interpolation algorithms, namely, bicubic and triangular interpolation. Two reanalysis datasets ERA5 and JRA55 providing correspondingly the finest and the coarsest spatial resolution were examined.

Comparison of temperatures interpolated to the station location revealed a relatively small effect of a specific interpolation scheme on the result of interpolation. Differences between the monthly, season and annual mean temperature interpolated to the station location with the three algorithms ranged mostly within 0.1–0.3 °C and were thus more than an order of magnitude smaller than the observed spread in temperature values between the datasets. Corresponding differences between the trend estimates peaked at 0.017 °C / decade. This is also approximately an order of magnitude smaller than the typical values of temperature trends and station-to-station trend differences (see Figure 2 and the Results section below).

Worth noting in Figure 2 is a notable increase of approximately 1.5 °C in the annual mean temperature at Rothera station in the beginning of 2020s. This temperature increase is consistent with reports of anomalously high summer-time temperatures documented in recent years on the Antarctic Peninsula (e. g., González-Herrero et al., 2022). Another interesting feature evident from Figure 2 is a strong rise of approximately 3 °C in the CFSR annual mean temperature at Dumont-Durville from 2011 onwards.

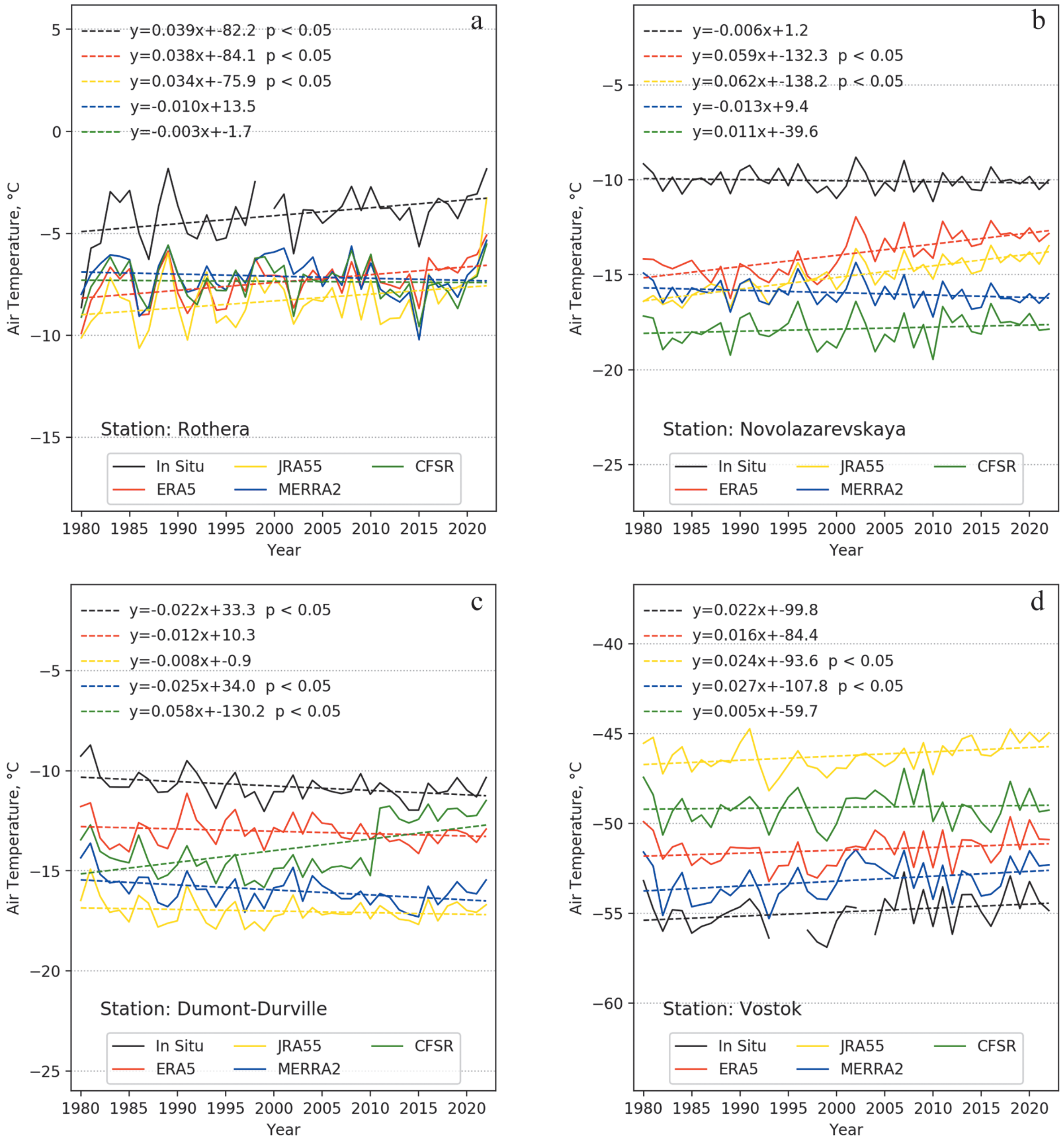

Fig. 2 – Time series of annual mean near-surface air temperature from in situ data and four reanalysis datasets for four Antarctic stations **a**) Rothera (listed No. 5 in Table 1 and shown under the same number in Figure 1; **b**) Novolozarevskaya (8); **c**) Dumont-Durville (14); and **d**) Vostok (15). Trends in the air temperature records over the 1980–2022 time period are shown with dashed lines

This temperature increase, along with the positive trend in the CFSR dataset driven by this increase, is not supported by temperature records in other reanalysis datasets, or in situ records, and thus is likely spurious. A similar temperature increase has been identified in CFSR records at several other coastal locations in East Antarctica, namely Suowa, Mawson, Mirny, and Casey. The fact that this change occurred concurrently with the transition from reprocessed to the operational CFSR data records suggests that it may be caused by differences in the model implementation in the two environments and/or differences in the input datasets used. However, the true reason for the observed inconsistency in the CFSR dataset remains to be determined.

Figure 3 presents the estimated annual mean temperature trends for all station locations and all analyzed datasets. The standard errors of the trend estimate, also shown in Figure 3, are determined by interannual temperature variations and generally range from 0.08 to 0.13 °C/decade. Trends inferred from in situ data (shown in black) exhibit a clear prevalence of upward tendencies in the air temperature records. Among the 18 Antarctic stations examined, 12 stations show positive trends, with positive trends at 7 stations being statistically significant ($p < 0.05$). This finding aligns with the recent studies of Turner et al., (2019) and Wang et al., (2016) who observed positive temperature trends at 13 out of 17 and 8 stations out of 13 Antarctic stations, respectively. The predominance of warming tendencies is further supported by a positive shift in the range of trend values, extending from –0.22±0.09 °C/decade at Dumont-Durville to 0.40±0.09 °C/decade at Faraday/Vernadsky, as well as by a positive mean trend value across all stations of 0.11 °C/decade.

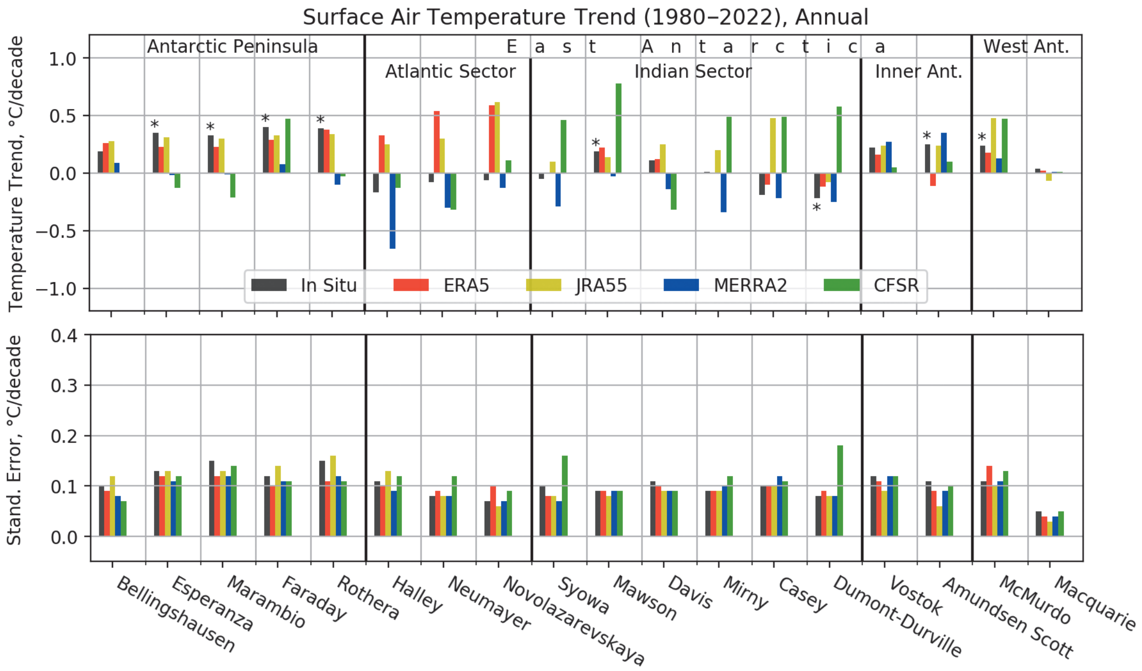

Fig. 3 – Trends in the annual mean-surface air temperature over 1980–2021 time period and corresponding trend standard errors at the ground station locations in Antarctica determined from reanalysis datasets and from in situ data. Statistically significant trends in in situ data are marked with an asterisk (*)

Consistent with earlier research (e. g., Carrasco, 2013; Turner et al., 2019), the Antarctic Peninsula stands out as the fastest warming region. Trends in the annual mean temperature in this region range from 0.19 to 0.40 °C/decade, with trend values at four out of five locations being statistically significant. Somewhat faster warming is observed at the stations on the western side of the Antarctic Peninsula (Faraday, Rothera) than at its northern tip (Bellingshausen, Esperanza, Marambio). Upward trends in excess of 0.2 °C/decade are also evident in Inner Antarctica (Amundsen Scott and Vostok) and in West Antarctica (McMurdo). Coastal areas of East Antarctica demonstrate mixed and relatively smaller temperature trends ranging from –0.22 to +0.19 °C/decade. The spatial distribution of trends in this region follows a wavelike pattern, with warming tendencies prevailing in the Atlantic Ocean sector and in the eastern part of the Indian Ocean sector of Antarctica, while cooling trends dominate in the eastern and central part of the Indian Ocean sector. This trend pattern is also evident in Figure 1.

Larger regional variations are inherent in seasonal mean air temperature trends inferred from in situ-data (Figure 4). On the Antarctic Peninsula, positive trends persist in all seasons except summer, with warming rates peaking at 0.7–0.8 °C/decade during the austral autumn and winter. Interestingly, in winter, the western coast of the Antarctic Peninsula exhibits stronger positive trends compared to its northern tip, while in autumn, the pattern reverses. In situ temperature trends remain consistently positive throughout the year in Inner Antarctica (Vostok, Amundsen Scott) and in the coastal West Antarctica (McMurdo). The strongest warming in these regions falls onto the austral spring. In contrast, the coastal areas of East Antarctica experience predominantly downward trends in all seasons except spring. The most pronounced cooling in this region occurs in winter: At this time of the year, a statistically significant negative trend of over –0.40 °C/decade is observed at four stations, Halley, Neumayer, Casey and Dumont-Duirvlle.

Most peculiarities of identified in situ temperature trends in Antarctica agree to the results of previous assessments. This concerns, in particular, the pronounced warming of the Antarctic Peninsula, the warming trends in West Antarctica and the mixed trends in the coastal areas of East Antarctica (Turner et al., 2019; Zhu et al., 2021; Carrasco, 2013; Clem et al., 2020; Bromwich et al., 2013). Consistent with the results of this study, autumn and winter were often associated with the strongest warming in the Antarctic Peninsula, largest positive trends in the West Antarctica were reported in the spring season, while no substantial trends were observed in summer. This qualitative agreement is not surprising since most studies sited above relied on in situ temperature records from the same READER dataset.

Differences in the trend estimates are mostly associated with different time periods considered in the analysis. To illustrate this, Table 3 compares our estimates of trends in the in situ annual mean temperature over the 1980–2022 time period with similar estimates of Turner et al. (2019). The latter study utilized observations at a similar set of Antarctic ground stations over a somewhat shorter timeframe spanning from 1979 to 2018. Matching estimates were available for 16 out of 18 locations used in our analysis. This enables a meaningful comparison of the two studies.

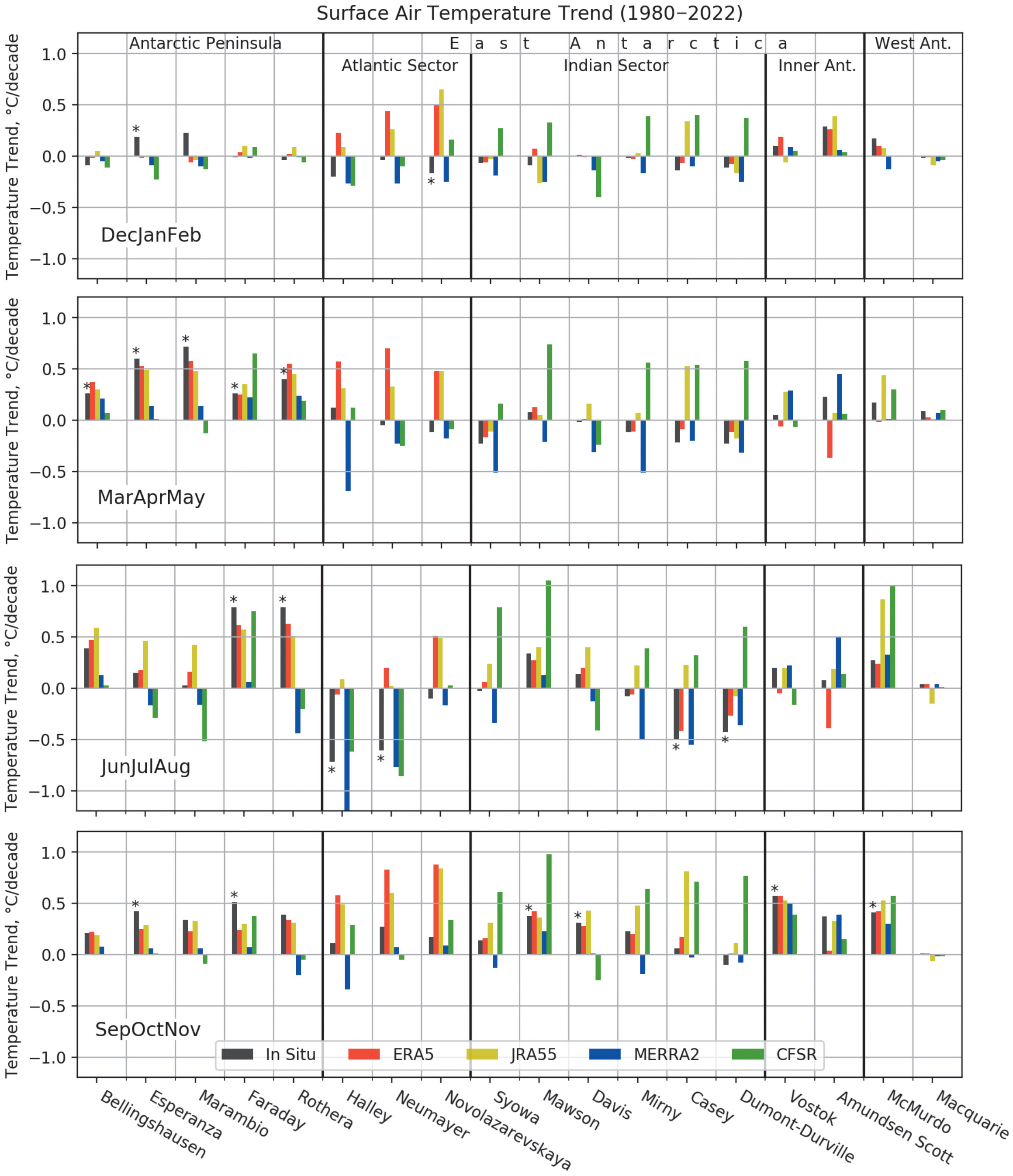

Fig. 4 – Trends in the seasonal mean near-surface air temperature over 1980–2021 time period determined from reanalysis datasets and from in situ data. Statistically significant trends in situ data are marked with an asterisk (*)

Table 3 – Trends in the annual temperature at Antarctic stations reported by Turner et al. (2019) for the 1979–2018 time period and estimated in this study for the 1980–2022 time period. Statistically significant trends ($p < 0.05$) are shown in bold. See Table 1 for the Region codes

No. in Table 1 and Fig.1	**Station**	**Region**	**Temperature Trend, °C/decade**		**Trend Change, °C/decade**
			Turner et al., (2019) 1979–2018	**This study 1980–2022**	
1	Bellingshausen	AP	0.09	0.19	+0.10
2	Esperanza	AP	0.23	0.35	+0.12
3	Marambio	AP	0.21	0.33	+0.12
4	Faraday/Vernadsky	AP	0.39	0.40	+0.01
5	Rothera	AP	0.38	0.39	+0.01
6	Neumayer	AS-EA	–0.04	–0.08	–0.04
7	Novolazarevskaya	AS-EA	–0.04	–0.06	–0.02
8	Syowa	IS-EA	–0.09	–0.05	+0.04
9	Mawson	IS-EA	0.08	0.19	+0.11
10	Davis	IS-EA	0.10	0.11	+0.01
11	Mirny	IS-EA	–0.08	0.00	+0.08
12	Casey	IS-EA	**–0.26**	–0.19	+0.07
13	Dumont Durville	IS-EA	**–0.27**	**–0.22**	+0.05
14	Vostok	IA-EA	0.21	0.22	+0.01
15	Amundsen Scott	IA-EA	0.29	0.25	–0.04
16	McMurdo/Scott Base	PS-WA	0.11	0.24	+0.13

As seen from Table 3, at 13 of 16 stations (or approximately in 80 % of all cases) there is a positive difference between the most up to date trend estimates and trends derived from temperature records ending a few years earlier. Among these cases, at nine places positive temperature trends strengthened and at four places negative trends weakened. The warming acceleration was most notable at the northern tip of the Antarctic Peninsula (Bellingshausen, Esperanza and Marambio) where positive trends increased by over 0.10 °C/decade from 1979–2018 to 1980–2022. Given trend values of 0.09 to 0.23 °C/decade between 1979 and 2018, this converts to approximately 50 to 100 % increase in the trend magnitude. Besides the Antarctic Peninsula, there is evidence of accelerated warming or a switch from cooling to warming tendency at all coastal locations in the Indian Ocean sector of East Antarctica, at McMurdo station in West Antarctica and at Vostok in Inner Antarctica. Only three stations – Neumayer and Novolazarevskaya in the Atlantic Ocean sector of East Antarctica, and Amundsen-Scott at the South Pole – demonstrate a marginal reduction of positive trends or an increased cooling. These instances, however, have little effect on the overall pattern of trend change where the opposing tendencies prevail.

Compared to station data, reanalysis datasets offer continuous in-time records of the near- surface air temperature. This eliminates possible uncertainty due to gaps in the time series. In this study, monthly mean temperature values over the 1980–2022 time period from all four reanalysis datasets – ERA5, JRA55, MERRA2 and CFSR – have been utilized to estimate trends in the annual, seasonal and monthly mean near-surface air temperature. Similar to the temperature values, trends estimated at model grid points adjacent to each station were interpolated to the station location using a bilinear interpolation technique. Figures 3 and 4 present temperature trends estimated from reanalysis and station data.

Analysis of the graphs in Figure 3 reveals that temperature trends derived from the reanalysis datasets are generally capable of reproducing in situ data, albeit with varying degrees of success and accuracy. Only at four stations, Bellingshausen, Faraday, Vostok and McMurdo, all reanalysis datasets agree to in situ data on the upward temperature trend. A relatively close match between the model and in situ data is achieved at Amundsen Scott, where the positive statistically significant temperature trend in in situ data is supported by all models except ERA5. In the Antarctic Peninsula warming trends observed on the ground are confirmed only by ERA5 and JRA55, while MERRA2 and CFSR indicate either neutral or weakly negative trends.

Discrepancies between in situ and model data, as well as between individual reanalysis datasets in the trend magnitude and direction increase in the coastal locations of East Antarctica. ERA5 successfully reproduces the trend sign at all locations in the Indian Ocean sector of Antarctica, but completely fails to do so in the Atlantic sector. Similar behavior is observed in JRA55. MERRA2 exhibits a strong cooling trend, whereas CSFR indicates predominantly warming trends over the coastal areas of East Antarctica, both contradicting the station data.

Reanalysis datasets only partially reflect the seasonal trend patterns seen in the observational records. They support the observed pronounced warming over the Antarctic Peninsula during the austral fall season, as well as the warming trends in Inner Antarctica and West Antarctica in spring. As with the station data, reanalysis-based temperature trends decrease in summer and become mostly positive in spring. In winter, complete agreement between all reanalysis datasets and the station data in terms of the trend direction is only achieved at three out of 18 locations: Bellingshausen, Mawson, and McMurdo. In summer, this number decreases to two.

Table 4 presents the statistical comparison between reanalysis trends and the corresponding trends derived from in situ data, aggregated across all locations. For each reanalysis dataset, we calculated the mean bias, root-mean-square error (RMSE), and the fraction of correctly identified trend signs in comparison to the in situ data. Error statistics for the annual mean trends were established by aggregating the error estimates across all stations included in the analysis, while the 12-month mean values were obtained by averaging the error estimates across both the stations and the months of the year. As shown in Table 4, among all reanalysis datasets, ERA5 exhibits the closest overall match to the in situ trend estimates. ERA5 demonstrates the lowest RMSE values of 0.27 and 0.22 °C/decade for the annual and monthly trend values, respectively. It also shows the largest fraction of correctly identified trend signs (0.78 and 0.80, respectively) and a fairly small bias of 0.07 °C/decade in both cases.

Table 4 – Statistics of trends in the annual mean air temperature at station location and performance metrics of reanalysis datasets for the annual mean and monthly air temperature trends

Metrics	**Aggregated Trend Statistics for Annual Mean Air Temperature at Station Locations**				
	In situ	**ERA5**	**JRA55**	**MERRA2**	**CSFR**
Mean (°C/decade)	0.11	0.18	0.26	–0.09	0.16
RMSD (°C/decade)	0.20	0.20	0.17	0.23	0.33
Annual Trend Agreement Statistics at Station Locations: Reanalysis vs In Situ					
Mean bias (°C/decade)	–	0.07	0.15	–0.19	0.05
RMSE (°C/decade)	–	0.27	0.28	0.28	0.41
Matching trend sign fraction	–	0.78	0.67	0.67	0.500
12-Month Trend Agreement Statistics at Station Locations: Reanalysis vs In Situ					
Mean bias (°C/decade)	–	0.07	0.16	–0.19	0.06
RMSE (°C/decade)	–	0.22	0.30	0.28	0.41
Matching trend sign fraction	–	0.80	0.70	0.78	0.60

Compared to ERA5, JRA55 and MERRA2 exhibit similar trend RMSE values with respect to in situ data but noticeably larger biases. On the opposite, trends inferred from CFSR match in situ observations fairly well in terms of the mean trend value across all stations but demonstrate much larger RMSE values. Notably, even in ERA5, the estimated trend uncertainty (as indicated by RMSE) exceeds the trend variability across the stations (as indicated by RMSD). This implies the limited ability of reanalysis datasets to accurately reproduce station-to station trend differences. Therefore, relatively small spatial peculiarities (below 0.2–0.3 °C/decade) in the distribution of annual and seasonal temperature trends inferred from reanalysis datasets should be treated with caution.

Figure 5 illustrates seasonal changes of performance of the four reanalysis datasets with respect to the temperature trends observed in situ. The statistics includes the mean bias, the root-mean-square error and the fraction of correct trend sign estimates aggregated over all Antarctic stations. The performance estimates reveal a distinct seasonal pattern, where the agreement with in situ data improves during the austral summer months and decreases in winter. As can be seen from the graphs in Figure 5, MERRA2 stands out with a strong negative trend bias in all months of the year. Evidence of the "cold bias" in Antarctic temperature trends estimated from MERRA2 was also provided by Simmons et al., (2017).

Trend estimates with JRA55 data are relatively accurate in summer but demonstrate a considerable positive bias in excess of 0.2 °C/decade in winter. CFSR is characterized by a relatively small bias in all months of the year, but stands out with large RMSE, particularly during the colder period of the year. Compared to other reanalysis datasets, ERA5 demonstrates the most favorable performance in terms of monthly trend estimates. It exhibits a relatively small bias, below 0.15 °C/decade, with respect to the station data, the smallest RMSE in most of the months and consistently high, above 0.6, fraction of correctly identified trend signs throughout the year.

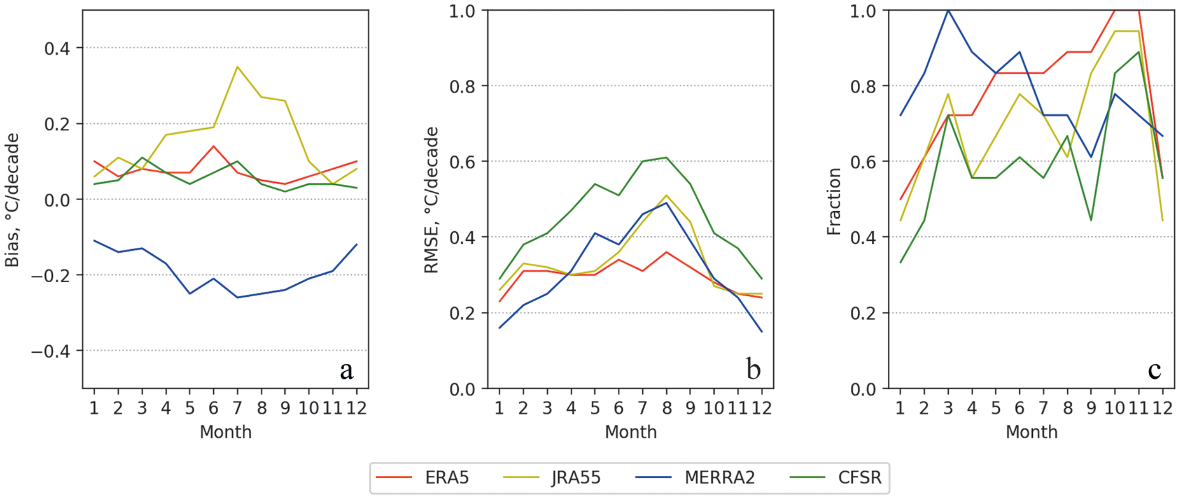

Fig. 5 – Mean bias (**a**), root-mean-square error (**b**) and the fraction of correct trend sign (**c**) of monthly mean air temperature trends in the reanalysis datasets vs corresponding trends in the in situ data

Discussion and Conclusion

Results presented in our study reveal a strong regional and seasonal variability of the trends in the near-surface air temperature in Antarctica. The magnitude and distinctive characteristics of temperature trends in the Antarctic station records over the last 43 years align well with the findings of previous studies, albeit with shorter temperature records. This includes notable warming in the Antarctic Peninsula, relatively smaller yet consistent upward temperature trends at stations located in Inner and West Antarctica, and mixed weaker trends in the coastal region of East Antarctica. The most wide spread temperature increase across Antarctica ground stations occurred in the spring season, summer-time trends were the least pronounced, while the strongest warming in the Antarctic Peninsula regions was associated with the winter and fall seasons.

The overall strong qualitative agreement of trend estimates in in situ data is not surprising since most studies of this type rely on the same READER dataset. Differences in the derived trend values primarily arise from different time periods considered in the analysis. In this study, in situ temperature trends estimated for the 1980–2022 time period turned to be mostly larger positive or weaker negative than trends inferred from the temperature records that spanned a similar time frame but ended several years earlier. This suggests an overall strengthening of warming tendencies across the continent. The warming acceleration was most pronounced over the Antarctic Peninsula, especially in its northern tip. Anomalously high summer-time temperatures observed over this region in the last two to three years might have contributed to this trend.

The physical mechanisms determining peculiarities of the temperature trends in Antarctica have been discussed in a number of earlier studies. Factors thought to be contributing to or driving long-term temperature changes include radiative forcing due to the increase of greenhouse gas emission, stratospheric ozone depletion (Wang et al., 2014), increase in the sea surface temperature in the tropics (Ding and Steig, 2013), as well as associated changes in the atmospheric circulation and in the sea ice concentration. Strengthening of Antarctic westerlies due to persisting positive phase of the Southern Annual Mode in the last four decades as well as deepening of the Amundsen Sea Low and associated increase in the cyclone activity are believed to cause an accelerated warming of the Antarctic Peninsula region (Watcher et al., 2020; Turner et al., 2013). Over the rest of the Antarctic coastal zone stronger eastward and northward winds pushing ice away from the shore stimulate the development of ice in the coastal areas and thus cause cooling of the air. Changing wind patterns and temperatures in the course of the year cause a complex pattern of seasonal temperature trends in Antarctica seen in particular from the results of our study.

Reanalysis datasets demonstrated a good correlation with station data with respect to year-to-year changes in air temperature but were less effective in reproducing long-term temperature trends. Among all reanalysis datasets included in the study, ERA5 provided the best match to in situ data on the trends in the annual and seasonal mean temperature, followed by JRA55. A strong negative bias was identified in MERRA2 trend estimates as compared to the station data, whereas CFSR exhibited large scatter in the trend estimates around the station data. The better performance of ERA5 may be partially attributed to its higher spatial resolution compared to the other reanalysis datasets.

Still, even in ERA5, discrepancies in the annual mean trend values between the reanalysis and in situ data exceeded 0.2 °C/decade. This is approximately twice the magnitude of the mean temperature trend value across all stations in Antarctica and is close to the magnitude of a typical station-to-station trend contrast. These numbers suggest a limited ability of the reanalysis datasets to accurately reproduce the spatial distribution of the temperature trends across the continent. Considering that some station data are included in the reanalysis schemes, broader characterization of the trend spatial patterns away from the station locations may be associated with even larger uncertainties.

The network of ground stations with sufficiently long uninterrupted records of surface temperature is sparse and these stations are unevenly distributed across the Antarctic continent. More than a quarter of the stations belong to the Antarctic Peninsula which is one of the fastest warming places in Antarctica. As a result, trends averaged across all station locations included in this study (0.11 °C/decade from the station data and 0.16 °C/decade from ERA5) are likely to be positively biased with respect to the true area-averaged continental-scale temperature trends and can hardly be viewed as their adequate estimate.

A noticeable progress has been achieved in the last two decades in expanding the network of automated ground-based weather stations. However, more time is required for records from these stations to reach the duration sufficient for climate applications. Besides, adding ground stations to the network would not improve the Southern Ocean coverage where satellite data remain the primary source of information on the surface temperature. This emphasizes the importance of further enhancement of reanalysis schemes and corresponding datasets to enhance their ability in reproducing long-term air temperature changes and trends in the Antarctic region.

Acknowledgements: The authors would like to thank two anonymous reviewers for critically reading the paper. Comments and suggestions of the reviewers helped to substantially improve and clarify the manuscript.

References

1. Amesbury, J. M., T. P. Roland, J. Royles, D. A. Hodgson, P. Convey, H. Griffiths, and D. J. Charman, 2017: Widespread biological response to rapid warming on the Antarctic Peninsula. *Current Biology*, **27**, 1616–1622.
2. Bintanja, R., G. J. van Oldenborgh, S. S. Drijfhout, B. Wouters, and C. A. Katsman, 2013: Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion. *Nature Geoscience*, **6** (5), 376–379.
3. Bozkurt, D., D. H. Bromwich, J. Carrasco, K. M. Hines, J. C. Maureira, and R. Rondanelli, 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.
4. Bradley, A., D. Bett, C. R. Williams, R. Arthern, P. Holland, and J. De Rydt, 2023: (How) can we attribute West Antarctic ice mass loss to climate change? *Copernicus Meetings, EGU23-8309*, 2023 Feb 20.
5. Bromwich, D. H., J. P. Nicolas, A. J. Monaghan, M. A. Lazzara, L. M. Keller, G. A. Weidner, and A. B. Wilson, 2013: Correction: Corrigendum: Central West Antarctica among the most rapidly warming regions on Earth. *Nature Geoscience,* **6**, 139–145.
6. Cannone, N., F. Malfasi, S. E. Favero-Longo, P. Convey, and M. Guglielmin, 2022: Acceleration of climate warming and plant dynamics in Antarctica. *Current Biology*, **32** (7), 1599–1606.
7. Carrasco, J. F., 2013: Decadal changes in the near-surface air temperature in the Western side of the Antarctic Peninsula. *Atmospheric and Climate Sciences*, **3**, 33653.
8. Carter, J., A. Leeson, A. Orr, C. Kittel, and J. M. van Wessem, 2022: Variability in Antarctic surface climatology across regional climate models and reanalysis datasets. *The Cryosphere*, **16** (9), 3815–3841.
9. Clem, K. R., R. L. Fogt, J. Turner, B. R. Lintner, G. L. Marshall, J. R. Miller, and J. A. Renwick, 2020: Record warming at the South Pole during the past three decades. *Nature Climate Change,* **10**, 762–770.
10. Cook, A. J., P. R. Holland, M. P. Meredith, T. Murray, A. Luckman, and D. G. Vaughan, 2016: Ocean forcing of glacier retreat in the western Antarctic Peninsula. *Science*, **353**, 283–286.
11. Ding, Q. and E. J. Steig, 2013: Temperature change on the Antarctic Peninsula linked to the tropical Pacific. *Journal of Climate*, **26** (19), 7570–7585.
12. Eayrs, C., X. Li, M. N. Raphael, and D. M. Holland, 2021: Rapid decline in Antarctic sea ice in recent years hints at future change. *Nature Geoscience*, **14** (7), 460–464.
13. Gelaro, R., W. McCarty, M. J. Suárez, R. Todling, A. Molod, L. Takacs, C. A. Randles, A. Darmenov, M. G. Bosilovich, R. Reichle, K. Wargan, L. Coy, R. Cullather, C. Draper, S. Akella, V. Buchard, A. Conaty, A. M. da Silva, W. Gu, G.-K. Kim, R. Koster, R. Lucchesi, D. Merkova, J. E. Nielsen, G. Partyka, S. Pawson, W. Putman, M. Rienecker, S. D. Schubert, M. Sienkiewicz, and B. Zhao, 2017: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA2). *Journal of Climate*, **30**, 5419–5454.
14. Gille, S. T., 2008: Decadal-scale temperature trends in the southern Hemisphere Ocean. *Journal of Climate*, **21**, 4749–4765.

15. Guglielmin, M., M. Dalle Fratte, and N. Cannone, 2014: Permafrost warming and vegetation changes in continental Antarctica. *Environmental Research Letters*, **9** (4), 045001.
16. Gonzalez, S. and D. Fortuny, 2018: How robust are the temperature trends on the Antarctic Peninsula? *Antarctic Science*, **30** (5), 322–328, https://doi.org/10.1017/S0954102018000251.
17. González-Herrero, S., D. Barriopedro, R. M. Trigo, J. A. Lopez-Bustins, and M. Olivia, 2022: Climate warming amplified the 2020 record-breaking heatwave in the Antarctic Peninsula. *Communications, Earth and Environment,* **3**, 122.
18. Hersbach H., P. de Rosnay, B. Bell, D. Schepers, A. Simmons, C. Soci, S. Abdalla, M. Alonso-Balmaseda, G. Balsamo, P. Bechtold, P. Berrisford, J.-R. Bidlot, E. de Boisséson, M. Bonavita, P. Browne, R. Buizza, P. Dahlgren, D. Dee, R. Dragani, M. Diamantakis, J. Flemming, C. Ho, J.-H. Kim, H.-S. Kim, C.-H. Sui, and D.-Y. Gong, 2018: Possible influence of the Antarctic Oscillation on tropical cyclone activity in the western North Pacific. *Journal of Geophysical Research*, **110**, D19104, https://doi.org/10.1029/2005JD005766.
19. Hobbs, W. R., R. Massom, S. Stammerjohn, P. Reid, G. Williams, and W. Meier, 2016: A review of recent changes in Southern Ocean sea ice, their drivers and forcings. *Global and Planetary Change*, **143**, 228–250.
20. Huai, B., Y. Wang, M. Ding, J. Zhang, and X. Dong, 2019: An assessment of recent global atmospheric reanalyses for Antarctic near surface air temperature. *Atmospheric Research*, **226**, 181–191.
21. Jones, P. D. and D. H. Lister, 2015: Antarctic near-surface air temperatures compared with ERA-Interim values since 1979. *International Journal of Climatology*, **35**, 1354–1366.
22. Kennicutt, M. C., S. L. Chown, J. J. Cassano, D. Liggett, L. S. Peck, R. Massom, S. R. Rintoul, J. Storey, D. G. Vaughan, T. J. Wilson, and I. Allison, 2015: A roadmap for Antarctic and Southern Ocean science for the next two decades and beyond. *Antarctic Science*, **27**, 3–18.
23. Kobayashi, S., Y. Ota, Y. Harada, A. Ebita, M. Moriya, H. Onoda, K. Onogi, H. Kamahori, C. Kobayashi, H. Endo, K. Miyaoka, and K. Takahashi, 2015: The JRA-55 Reanalysis: General Specifications and Basic Characteristics. *Journal of Meteorological Society Japan,* **93**, 5–48.
24. Marshall, G. J., D. W. J. Thompson, and M. R. van den Broeke, 2017: The signature of Southern Hemisphere atmospheric circulation patterns in Antarctic precipitation. *Geophysical Research Letters*, **44**, 11,580– 11,589, https://doi.org/10.1002/2017GL075998.
25. Medley, B. and E. R. Thomas, 2019: Increased snowfall over the Antarctic Ice Sheet mitigated twentieth-century sea-level rise. *Nature Climate Change,* **9**, 34–39.
26. Menezes, V. V., A. A. McDonald, and C. Schatzman, 2017: Accelerated freshening of Antarctic bottom water over the last decade in the Southern Indian Ocean. *Science Advances*, **3** (1), e1601426, https://doi.org/10.1126/sciadv.1601426.
27. Mokhov, I. I. and M. R. Parfenova, 2021: Relationship of the Extent of Antarctic and Arctic Ice with Temperature Changes, 1979–2020. *Doklady Earth Science,* **496**, 66–71, https://doi.org/10.1134/S1028334X21010153.
28. Nicolas, J. P. and D. H. Bromwich, 2011: New reconstruction of Antarctic near-surface temperatures: Multidecadal trends and reliability of global reanalyses. *Journal of Climate*, **24** (4), 926–945.
29. Pinkerton, M. H., P. W. Boyd, S. Deppeler, A. Hayward, J. Höfer, and S. Moreau, 2021: Evidence for the impact of climate change on primary producers in the Southern Ocean. *Frontiers in Ecology and Evolution,* **9**, 592027.
30. Raphael, M. N. and M. S. Handcock, 2022: A new record minimum for Antarctic sea ice. *Nature Reviews Earth and Environment,* **3**, 215–216, https://doi.org/10.1038/s43017-022-00281-0.
31. Romanova, N. A. and P. Yu. Romanov, 2019: Antarctic wind intensification as inferred from the NCEP/NCAR reanalysis data. *Journal of Oceanological Research*, **48** (3), 96–108.

32. Romanov, P. Yu. and N. A. Romanova, 2021: Sea-level pressure trends in the Southern Ocean and Antarctica from reanalysis and in situ data. *Journal of Oceanological Research*, **49** (4), 63–85.
33. Saha, S., S. Moorthi, H. L. Pan, X. Wu, J. Wang, S. Nadiga, P. Tripp, R. Kistler, J. Woollen, D. Behringer, and H. Liu, 2010: The NCEP climate forecast system reanalysis. *Bulletin of the American Meteorological Society*, **91** (8), 1015–1058.
34. Saha, S., S. Moorthi, X. Wu, J. Wang, S. Nadiga, P. Tripp, D. Behringer, Y. T. Hou, H. Y. Chuang, M. Iredell, and M. Ek, 2014: The NCEP climate forecast system version 2. *Journal of Climate*, **27** (6), 2185–2208.
35. Simmons, A. J., P. Berrishford, D. P. Dee, H. Hersbach, S. Hirahara, and J.-N. Thepaut, 2017: A reassessment of temperature variations and trends from global reanalyses and monthly surface climatological datasets. *Quarterly Journal of the royal Meteorological Society*, **143**, 101–119.
36. Smith, K. E., R. B. Aronson, B. V. Steffel, M. O. Amsler, S. Thatje, H. Singh, J. Anderson, C. J. Brothers, A. Brown, D. S. Ellis, J. N. Havenhand, W. R. James, P.-O. Moksnes, A. W. Randolph, T. Sayre-McCord, and J. B. McClintock, 2017: Climate change and the threat of novel marine predators in Antarctica. *Ecosphere,* **8** (11), e02017. 10.1002/ecs2.2017.
37. Turner, J., G. J. Marshall, K. Clem, S. Colwell, T. Phillips, and H. Lu, 2019: Antarctic temperature variability and change from station data. *International Journal of Climatology,* **40**, 2986–3007, https://doi.org/10.1002/joc.6378.
38. Turner, J., T. Phillips, J. S. Hosking, G. J. Marshall, and A. Orr, 2013: The Amundsen Sea low. *International Journal of Climatology*, **33**, 1818–1829, https://doi.org/10.1002/joc.3558.
39. Turner, J., H. Lu, I. White, J. C. King, T. Phillips, J. S. Hosking., T. J. Bracegirdle, G. J. Marshall, R. Mulvaney, and P. Deb, 2016: Absence of 21st century warming on Antarctic Peninsula consistent with natural variability. *Nature,* **535**, 411–415.
40. Wang, G., W. Cai, and A. Purich, 2014: Trends in Southern Hemisphere wind-driven circulation in CMIP5 models over the 21st century: Ozone recovery versus greenhouse forcing. *Journal of Geophysical Research: Oceans*, **119** (5), 2974–2986.
41. Wang, Y., D. Zhou, A. Bunde, and S. Havlin, 2016: Testing reanalysis data sets in Antarctica: Trends, persistence properties, and trend significance. *Journal of Geophysical Research*: *Atmospheres*, **121** (21), 12,839–12,855.
42. Wachter, P., C. Beck, A. Philip, K. Höppner, and J. Jacobeit, 2020: Spatiotemporal variability of the Southern Annular Mode and its influence on Antarctic surface temperatures. *Journal of Geophysical Research: Atmospheres*, **125** (23), e2020JD033818.
43. Weller, G., 1998: Regional impacts of climate change in Arctic and Antarctic. *Annals of Glaciology*, **27**, 543–552.
44. WMO, 2023: Antarctic sea ice reaches lowest winter extent on record. [online] Available at: https://public.wmo.int/en/media/news/antarctic-sea-ice-reaches-lowest-winter-extent-record [Accessed 2 Oct. 2023].
45. Yang, Y., Q. Li, Z. Song, W. Sun, and W. Dong, 2022: A comparison of global surface temperature variability, extremes and warming trend using reanalysis datasets and CMST-Interim. *International Journal of Climatology*, **42** (11), 5609–5628.
46. Yu, L., Z. Zhang, M. Zhou, S. Zhong, D. Lenschow, H. Hsu, H. Wu, and B. Sun, 2010: Validation of ECMWF and NCEP-NCAR reanalysis data in Antarctica. *Advances in Atmospheric Sciences,* **27**, 1151–1168.
47. Zhang, Y., Y. Wang, and S. Hou, 2022: Reliability of Antarctic air temperature changes from Polar WRF: A comparison with observations and MAR outputs. *Atmospheric Research*, **266**, 105967.
48. Zhu, J., A. Xie, X. Qin, Y. Wang, B. Xu, and Y. Wang, 2021: An Assessment of ERA5 Reanalysis for Antarctic Near-Surface Air Temperature. *Atmosphere,* **12**, 217.

Submitted 07.07.2023, accepted 06.10.2023.
For citation: Romanov, P. Yu. and N. A. Romanova, 2023: Recent trends in near-surface air temperature in Antarctica from reanalysis and station data. *Journal of Oceanological Research*, **51** (3), 84–105, https://doi.org/10.29006/1564-2291.JOR-2023.51(3).4.

ТЕКУЩИЕ ТРЕНДЫ ПРИПОВЕРХНОСТНОЙ ТЕМПЕРАТУРЫ ВОЗДУХА В АНТАРКТИДЕ ПО ДАННЫМ РЕАНАЛИЗА И НАЗЕМНЫХ СТАНЦИЙ

П. Ю. Романов[1], Н. А. Романова[2]

[1]CREST Institute, City University of New York,
160 Convent Ave, New York, NY 10031, USA,
e-mail: peter.romanov@noaa.gov;
[2] Институт океанологии им. П. П. Ширшова РАН,
Россия, 117997, Москва, Нахимовский проспект, 36,
e-mail: romanova@ocean.ru

В этом исследовании по данным наземных станций в Антарктике были построены оценки трендов приповерхностной температуры воздуха за период с 1980 по 2022 годы. Анализ наземных данных подтвердил преобладающие тенденции к потеплению на континенте: положительные тренды температуры были выявлены в рассмотренных данных 11 станций из 18. Тренды среднегодовой температуры воздуха достигают значений в 0.40 °C/декаду, при этом наиболее значительное потепление происходит на станциях, расположенных на Антарктическом полуострове, в Западной Антарктике и во внутриконтинентальной части Антарктики. В прибрежных районах Восточной Антарктики были обнаружены относительно слабые переменные по знаку температурные тренды. В годовом ходе весенний сезон выделяется наиболее устойчивыми по континенту положительными трендами температуры. Сравнение текущих значений трендов температуры с их более ранними оценками указывает на ускорение потепления в последние годы на большинстве антарктических станций. В работе были проанализированы четыре часто используемых набора данных реанализа – ERA5, JRA55, MERRA2 и CFSR с целью оценить их способность по точному воспроизведению трендов температуры наблюдаемых в натурных данных. Среди этих четырех наборов данных температурные тренды, полученные с помощью ERA5, показали наилучшее соответствие результатам измерений на станциях. Однако даже в ERA5 неопределенность в оценках трендов оказалась сравнимой с величиной изменчивости трендов между станциями. Это указывает на ограниченные возможности имеющихся данных реанализа для адекватной характеристики пространственных особенностей трендов температуры по всему континенту.

Ключевые слова: Антарктика, приповерхностная температура воздуха, данные наземных станций, данные реанализа, тренды температуры

Благодарности. Авторы хотели бы поблагодарить двух анонимных рецензентов за помощь в работе над статьей. Замечания и предложения рецензентов помогли существенно улучшить и уточнить рукопись.

Список литературы

1. *Amesbury J. M., Roland T. P., Royles J., Hodgson D. A., Convey P., Griffiths H., Charman D. J.* Widespread biological response to rapid warming on the Antarctic Peninsula // Current Biology. 2017. Vol. 27. P. 1616–1622.
2. *Bintanja R., van Oldenborgh G. J., Drijfhout S. S., Wouters B., Katsman C. A.* Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion // Nature Geoscience. 2013. Vol. 6 (5). P. 376–379.
3. *Bozkurt D., Bromwich D. H., Carrasco J., Hines K. M., Maureira J. C., Rondanelli R.* Recent near-surface temperature trends in the Antarctic Peninsula from observed, reanalysis and regional climate model data // Advances in Atmospheric Sciences. 2020. Vol. 37. P. 477–493.
4. *Bradley A., Bett D., Williams C. R., Arthern R., Holland P., De Rydt J.* (How) can we attribute West Antarctic ice mass loss to climate change? // Copernicus Meetings. No. EGU23-8309. 2023. Feb. 20.
5. *Bromwich D. H., Nicolas J. P., Monaghan A. J., Lazzara M. A., Keller L. M., Weidner G. A., Wilson A. B.* Correction: Corrigendum: Central West Antarctica among the most rapidly warming regions on Earth // Nature Geoscience. 2013. Vol. 6. P. 139–145.
6. *Cannone N., Malfasi F., Favero-Longo S. E., Convey P., Guglielmin M.* Acceleration of climate warming and plant dynamics in Antarctica // Current Biology. 2022. Vol. 32 (7). P. 1599–1606.
7. *Carrasco J. F.* Decadal changes in the near-surface air temperature in the Western side of the Antarctic Peninsula // Atmospheric and Climate Sciences. 2013. Vol. 3. P. 33653.
8. *Carter J., A. Leeson, A. Orr, C. Kittel and J. M. van Wessem* Variability in Antarctic surface climatology across regional climate models and reanalysis datasets // The Cryosphere. 2022. Vol. 16 (9). 3815–3841.
9. *Clem K. R., Fogt R. L., Turner J., Lintner B. R., Marshall G. L., Miller J. R., Renwick J. A.* Record warming at the South Pole during the past three decades // Nature Climate Change. 2020. Vol. 10. P. 762–770.
10. *Cook A. J., Holland P. R., Meredith M. P., Murray T., Luckman A., Vaughan D. G.* Ocean forcing of glacier retreat in the western Antarctic Peninsula // Science. 2016. Vol. 353. P. 283–286.
11. *Ding Q., Steig E. J.* Temperature change on the Antarctic Peninsula linked to the tropical Pacific // Journal of Climate. 2013. Vol. 26 (19). P. 7570–7585.
12. *Eayrs C., Li X., Raphael M. N., Holland D. M.* Rapid decline in Antarctic sea ice in recent years hints at future change // Nature Geoscience. 2021. Vol. 14 (7). P. 460–464.
13. *Gelaro R., W. McCarty W., Suárez M. J., Todling R., Molod A., Takacs L., Randles C. A., Darmenov A., Bosilovich M. G., Reichle R., Wargan K., Coy L., Cullather R., Draper C., Akella S., Buchard V., Conaty A.,da Silva A. M., Gu W., Kim G-K., Koster R., Lucchesi R., Merkova D., Nielsen J. E., Partyka G., Pawson S., Putman W., Rienecker M., Schubert S. D., Sienkiewicz M., Zhao B.* The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA2) // Journal of Climate. 2017. Vol. 30. P. 5419–5454.
14. *Gille S. T.* Decadal-scale temperature trends in the southern Hemisphere Ocean // Journal of Climate. 2008. Vol. 21. P. 4749–4765.
15. *Guglielmin M., Dalle Fratte M., Cannone N.* Permafrost warming and vegetation changes in continental Antarctica // Environmental Research Letters. 2014. Vol. 9 (4). P. 045001.
16. *Gonzalez S., Fortuny D.* How robust are the temperature trends on the Antarctic Peninsula? // Antarctic Science. 2018. Vol. 30 (5). P. 322–328. https://doi.org/10.1017/S0954102018000251.
17. *González-Herrero S., Barriopedro D., Trigo R. M., Lopez-Bustins J. A., Olivia M.* Climate warming amplified the 2020 record-breaking heatwave in the Antarctic Peninsula // Communications, Earth and Environment. 2020. Vol. 3. P. 122.

18. *Hersbach H., de Rosnay P., Bell B., Schepers D., Simmons A., Soci C., Abdalla S., Alonso-Balmaseda M., Balsamo G., Bechtold P., Berrisford P., Bidlot J.-R., de Boisséson E., Bonavita M., Browne P., Buizza R., Dahlgren P., Dee D., Dragani R., Diamantakis M., Flemming J., Ho C., Kim J.-H., Kim H.-S., Sui C.-H., Gong D.-Y.* Possible influence of the Antarctic Oscillation on tropical cyclone activity in the western North Pacific // Journal of Geophysical Research. 2005. Vol. 110. D19104. https://doi.org/10.1029/2005JD005766.
19. *Hobbs W. R., Massom R., Stammerjohn S., Reid P., Williams G., Meier W. A.* Review of recent changes in Southern Ocean sea ice, their drivers and forcings // Global and Planetary Change. 2016. Vol. 143. P. 228–250.
20. *Huai B., Wang Y., Ding M., Zhang J., Dong X.* An assessment of recent global atmospheric reanalyses for Antarctic near surface air temperature // Atmospheric Research. 2019. Vol. 226. P. 181–191.
21. *Jones P. D., Lister D. H.* Antarctic near-surface air temperatures compared with ERA-Interim values since 1979 // International Journal of Climatology. 2015. Vol. 35. P. 1354–1366.
22. *Kennicutt M. C., Chown S. L., Cassano J. J., Liggett D., Peck L. S., Massom R., Rintoul S. R., Storey J., Vaughan D. G., Wilson T. J., Allison I.* A roadmap for Antarctic and Southern Ocean science for the next two decades and beyond // Antarctic Science. 2015. Vol. 27. P. 3–18.
23. *Kobayashi S., Ota Y., Harada Y., Ebita A., Moriya M., Onoda H., Onogi K., Kamahori H., Kobayashi C., Endo H., Miyaoka K., Takahashi K.* The JRA-55 Reanalysis: General Specifications and Basic Characteristics // Journal of Meteorological Society Japan. 2015. Vol. 93. P. 5–48.
24. *Marshall G. J., Thompson D. W. J., van den Broeke M. R.* The signature of Southern Hemisphere atmospheric circulation patterns in Antarctic precipitation // Geophysical Research Letters. 2017. Vol. 44. P. 11,580–11,589. https://doi.org/10.1002/2017GL075998.
25. *Medley B., Thomas E. R.* Increased snowfall over the Antarctic Ice Sheet mitigated twentieth-century sea-level rise // Nature Climate Change. 2019. Vol. 9. P. 34–39.
26. *Menezes V. V., McDonald A. A., Schatzman C.* Accelerated freshening of Antarctic bottom water over the last decade in the Southern Indian Ocean // Science Advances. 2017. Vol. 3 (1). e1601426. https://doi.org/10.1126/sciadv.1601426.
27. *Mokhov I. I., Parfenova M. R.* Relationship of the Extent of Antarctic and Arctic Ice with Temperature Changes, 1979–2020 // Doklady Earth Science. 2012. Vol. 496. P. 66–71. https://doi.org/10.1134/S1028334X21010153.
28. *Nicolas J. P., Bromwich D. H.* New reconstruction of Antarctic near-surface temperatures: Multidecadal trends and reliability of global reanalyses // Journal of Climate. 2011. Vol. 24 (4). P. 926–945.
29. *Pinkerton M. H., Boyd P. W., Deppeler S., Hayward A., Höfer J., Moreau S.* Evidence for the impact of climate change on primary producers in the Southern Ocean // Frontiers in Ecology and Evolution. 2021. Vol. 9. P. 592027.
30. *Raphael M. N., Handcock M. S.* A new record minimum for Antarctic sea ice // Nature Reviews Earth and Environment. 2022. Vol. 3. P. 215–216. https://doi.org/10.1038/s43017-022-00281-0.
31. *Romanova N. A., Romanov P. Yu.* Antarctic wind intensification as inferred from the NCEP/NCAR reanalysis data // Journal of Oceanological Research. 2020. Vol. 48 (3). P. 96–108.
32. *Romanov P. Yu., Romanova N. A.* Sea-level pressure trends in the Southern Ocean and Antarctica from reanalysis and in situ data // Journal of Oceanological Research. 2021. Vol. 49 (4). P. 63–85.
33. *Saha S., Moorthi S., Pan H. L., Wu X., Wang J., Nadiga S., Tripp P., Kistler R., Woollen J., Behringer D., Liu H.* The NCEP climate forecast system reanalysis // Bulletin of the American Meteorological Society. 2010. Vol. 91 (8). P. 1015–1058.

34. *Saha S., Moorthi S., Wu X., Wang J., Nadiga S., Tripp P., Behringer D., Hou Y. T., Chuang H. Y., Iredell M., Ek M.* The NCEP climate forecast system version 2 // Journal of Climate. 2014. Vol. 27 (6). P. 2185–2208.
35. *Simmons A. J., Berrishford P., Dee D. P., Hersbach H., Hirahara S., Thepaut J.-N.* A reassessment of temperature variations and trends from global reanalyses and monthly surface climatological datasets // Quarterly Journal of the Royal Meteorological Society. 2017. Vol. 143. P. 101–119.
36. *Smith K. E., Aronson R. B., Steffel B. V., Amsler M. O., Thatje S., Singh H., Anderson J., Brothers C. J., Brown A., Ellis D. S., Havenhand J. N., James W. R., Moksnes P.-O., Randolph A. W., Sayre-McCord T., McClintock J. B.* Climate change and the threat of novel marine predators in Antarctica // Ecosphere. 2017. Vol. 8 (11). e02017. 10.1002/ecs2.2017.
37. *Turner J., Marshall G. J., Clem K., Colwell S., Phillips T., Lu H.* Antarctic temperature variability and change from station data // International Journal of Climatology. 2019. Vol. 40. P. 2986–3007. https://doi.org/10.1002/joc.6378.
38. *Turner J., Phillips T., Hosking J. S., Marshall G. J., Orr A.* The Amundsen Sea low // International Journal of Climatology. 2013. Vol. 33. P. 1818–1829. https://doi.org/10.1002/joc.3558.
39. *Turner J., Lu H., White I., King J. C., Phillips T., Hosking J. S., Bracegirdle T. J., Marshall G. J., Mulvaney R., Deb P.* Absence of 21st century warming on Antarctic Peninsula consistent with natural variability // Nature. 2016. Vol. 535. P. 411–415.
40. *Wang G., Cai W., Purich A.* Trends in Southern Hemisphere wind-driven circulation in CMIP5 models over the 21st century: Ozone recovery versus greenhouse forcing // Journal of Geophysical Research: Oceans. 2014. Vol. 119 (5). P. 2974–2986.
41. *Wang Y., Zhou D., Bunde A., Havlin S.* Testing reanalysis data sets in Antarctica: Trends, persistence properties, and trend significance // Journal of Geophysical Research: Atmospheres. 2016. Vol. 121 (21). P. 12,839–12,855.
42. *Wachter P., Beck C., Philip A., Höppner K., Jacobeit J.* Spatiotemporal variability of the Southern Annular Mode and its influence on Antarctic surface temperatures // Journal of Geophysical Research: Atmospheres. 2020. Vol. 125 (23). P. e2020JD033818.
43. *Weller G.* Regional impacts of climate change in Arctic and Antarctic // Annals of Glaciology. 1998. Vol. 27. P. 543–552.
44. *WMO.* Antarctic sea ice reaches lowest winter extent on record. [online] Available at: https://public.wmo.int/en/media/news/antarctic-sea-ice-reaches-lowest-winter-extent-record, 2003, [Accessed 2 Oct. 2023].
45. *Yang Y., Li Q., Song Z., Sun W., Dong W. A* comparison of global surface temperature variability, extremes and warming trend using reanalysis datasets and CMST-Interim // International Journal of Climatology. 2022. Vol. 42 (11). P. 5609–5628.
46. *Yu L., Zhang Z., Zhou M., Zhong S., Lenschow D., Hsu H., Wu H., Sun B.* Validation of ECMWF and NCEP-NCAR reanalysis data in Antarctica // Advances in Atmospheric Sciences. 2010. Vol. 27. P. 1151–1168.
47. *Zhang Y., Wang Y., Hou S.* Reliability of Antarctic air temperature changes from Polar WRF: A comparison with observations and MAR outputs // Atmospheric Research. 2022. Vol. 266. 105967.
48. *Zhu J., Xie A., Qin X., Wang Y., Xu B., Wang Y.* An Assessment of ERA5 Reanalysis for Antarctic Near-Surface Air Temperature // Atmosphere. 2021. Vol. 12. P. 217.

Статья поступила в редакцию 07.07.2023, одобрена к печати 06.10.2023.
Для цитирования: *Романов П. Ю., Романова Н. А.* Текущие тренды приповерхностной температуры воздуха в Антарктиде по данным реанализа и наземных станций // Океанологические исследования. 2023. Т. 51. № 3. С. 84–105. https://doi.org/10.29006/1564-2291.JOR-2023.51(3).4.