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Major Artifacts in ERA5 2-m Air Temperature Trends Over Antarctica Prior to and During the Modern Satellite Era

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Key Points:

- ERA5 air temperatures have spurious trends for most regions of Antarctica prior to 1979
- Artificial trend hotspots are present at three low elevation sites until the present
- ERA5 cannot be used for temperature climate change studies over Antarctica earlier than 1979 but can be selectively applied post 1979

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Global reanalyzes are widely used for investigations of Antarctic climate variability and change. The European Centre for Medium-Range Weather Forecasts 5th generation reanalysis (ERA5) is well regarded and spans 1940 to today. We investigate whether ERA5 reliably represents the 2-m air temperature trends across the 1940–2022 (83 years) period at seasonal and annual time scales. We compare ERA5 temperatures with an observation-based temperature reconstruction for Antarctica (RECON) that has monthly resolution for 1958–2022, the period of reliable observational availability. Results for individual stations are also examined. ERA5 anomalously warms Antarctica in relation RECON especially for the period prior to 1979 when satellite observations over the Southern Ocean were sparse. Trend hotspots that are shown to be artifacts are found at three locations and are present until today. The results demonstrate that ERA5 temperature trends can be questionable even today, but variability is well captured after 1979.

Plain Language Summary Reanalyzes are especially useful for describing and understanding the climate of regions where observations are few and far between. Reanalyzes are not actual conditions but approximations that have strengths as well as weaknesses. A continuing reanalysis challenge for higher latitudes of the Southern Hemisphere that has caused many previous artifacts is the transition from few satellite observations over the Southern Ocean prior to 1979 to the relative abundance since. Here we examine the 2-m air temperature from the latest global reanalysis from ECMWF for Antarctica and show that it is still challenged by the 1979 transition. ERA5 warms Antarctica much too rapidly especially prior to 1979 and contains artificial trend hotspots at three locations right up to the present. ERA5 cannot be used for Antarctic temperature climate change applications prior to 1979 but can be applied for this purpose after 1979 with appropriate caution.

1. Introduction

Near-surface (2 m) air temperature behavior is a primary indicator of climate change on Earth (e.g., Gulev et al., 2021). Antarctica is important to global climate through it being the dominant cold source on the planet (e.g., Papritz et al., 2015), being the origin for Antarctic Bottom Water, the densest water mass in the global ocean that directly links the hemispheres (e.g., Lee et al., 2019), and for the ice sheet's large contribution to sea level rise (e.g., Otosaka et al., 2023), among many other reasons. The sea ice around Antarctica abruptly decreased below the satellite-era average in 2016 and has been maintained at roughly that level through 2022 (Massonnet et al., 2023), suggesting the influence of anthropogenic climate change (Eayrs et al., 2021). Antarctic sea ice extent in 2023 through July set all time minimum records nearly every month (e.g., Siegert et al., 2023). Yet determining the near-surface temperature all over Antarctica from meteorological observations to determine climate variability and change is a challenge due the sparseness of the observing locations, and the harshness of the climate (e.g., Jones et al., 2019). Other approaches to determining near-surface temperature over Antarctica include skin temperature measurements from satellite observations in infrared wavelengths that are contaminated by cloud obscuration of the surface (e.g., Retamales-Muñoz et al., 2019), and indirect approaches such as water stable isotopes in precipitation, firn samples, and ice cores that are proxies of actual temperatures and come with their own strengths and limitations (e.g., Masson-Delmotte et al., 2008).

Reanalyzes employ short-term weather forecasts that then assimilate a wide variety of atmospheric observations to derive near-surface air temperatures at time scales of 1 hr or more and at space scales of 30 km or more. Evaluations of these reanalyzes over Antarctica have yielded promising results in reproducing the observed temperatures supplied to the reanalysis since 1979. For example, Gossart et al. (2019) evaluated the performance

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over Antarctica of 4 state-of-the-art reanalyzes: the European Centre for Medium-Range Weather Forecasts (ECMWF) 5th generation reanalysis (ERA5) and its predecessor ERA-Interim; the Climate Forecast System Reanalysis (CFSR), and the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2). They determined that ERA5 showed the smallest bias relative to the observations for 2000–2016. Spatially ERA5 was too warm in the interior (>1500 m elevation) by several degrees during winter, but well represented the annual cycle in the coastal regions and the Antarctic Peninsula. Broadly similar results were obtained by Zhu et al. (2021) who examined ERA5 in relation to ERA-Interim and station observations across Antarctica for 1979–2018. Neither study emphasized temperature trends that is the focus here for climate change considerations.

We consider Antarctic near-surface temperature trends in ERA5 on seasonal and annual time scales since the start of this reanalysis. ERA5 is widely used in Antarctic long-term climate change studies (e.g., Casado et al., 2023; Sato & Simmonds, 2021; Xie et al., 2023) and has been recently extended back to 1940 (Soci et al., 2024). Trends are problematic for reanalyzes because of the many data sources used that have inherent biases which are not always easy to correct (e.g., Hersbach et al., 2020). The change from very sparse satellite coverage over the Southern Ocean before 1979 to relatively abundant satellite coverage since has been particularly challenging for earlier global reanalyzes (e.g., Bromwich & Fogt, 2004). Here we compare the near surface 2-m temperature trends between ERA5 and a station-based reconstructed data set for 1958–2022 and focus on the 1979 satellite transition.

2. Data and Methods

ERA5 is the latest global reanalysis produced by ECMWF and succeeds ERA-Interim (Hersbach et al., 2020). It provides a detailed record of the behavior of the global atmosphere, land surface, and ocean waves and spans 1940-present. ERA5 has a spatial resolution of ∼31 km with 137 vertical levels and provides surface variables at hourly intervals with uncertainty estimates every 3 hr. An offline two-dimensional optimal interpolation scheme is used to analyze the 2-m air temperature field from temperature observations (Hersbach et al., 2020; Simmons et al., 2004, Appendix A); this analysis is not directly used in the reanalysis production. A preliminary reanalysis is produced within 5 days of real-time with the final version being available after ∼3 months. ERA5 features advances in ECMWF 4DVAR atmospheric data assimilation through 2016 especially related to satellite data, and better atmospheric physics and dynamics than ERA-Interim. Time varying greenhouse gas concentrations and the impacts of volcanic eruptions are considered. Sea surface temperatures and sea ice concentrations are specified from various sources. Here we use the ERA5 0.25° latitude-longitude 2-m temperature monthly data set from ECMWF. We also examined 2-m monthly temperatures from all the 10 members of the ERA5 ensemble (60 km resolution, 3-hr time resolution, 1958–2022) and ERA5-Land (9 km resolution, 1-hr time resolution, 1958–2022) and obtained very similar results to those presented below so no further discussion of these data sets is provided.

To test ERA5's spatial representation of Antarctic 2-m temperatures, an updated version of the near-surface temperature reconstruction by Nicolas and Bromwich (2014), termed RECON from now on, is employed. The original reconstruction relied on monthly temperature observations from 15 staffed stations across Antarctica that were extrapolated to the entire continent using the spatial variability described by the CFSR reanalysis. The reconstruction closely matched the station observations, was not impacted by anomalous temperature trends in the reanalysis and was verified against independent temperature observations. It spanned 1958–2012 at monthly intervals. For the updated version of Nicolas and Bromwich (2014) Belgrano station is employed instead of Halley Station because of the recently documented distortion of the Halley temperature record caused by the frequent relocation of the observation site (King et al., 2021). The ERA5 global reanalysis is employed to provide the spatial weights that extrapolate the station observations. ERA5 is a more modern reanalysis than CFSR and has fewer issues with anomalous temperature trends (Gossart et al., 2019); testing for the 1958–2012 period with the original 15 stations demonstrated that CFSR and ERA5 based spatial extrapolation produced very similar results (not shown). Monthly average 2-m temperatures from the 14 stations employed by Nicolas and Bromwich (2014) as well as Belgrano (Figure 1) were updated through 2022 primarily from the READER site. ERA5 weights and the updated station records were employed to produce the updated Nicolas and Bromwich (2014) temperature anomaly data set (relative to 1981–2010) that now spans the 65 years from 1958 to 2022 at monthly intervals. This data set is detailed and validated in a separate manuscript. The updated station records are used here to perform point-wise validations of ERA5 anomaly values that have been bilinearly interpolated from the surrounding 4 grid points to the station locations.

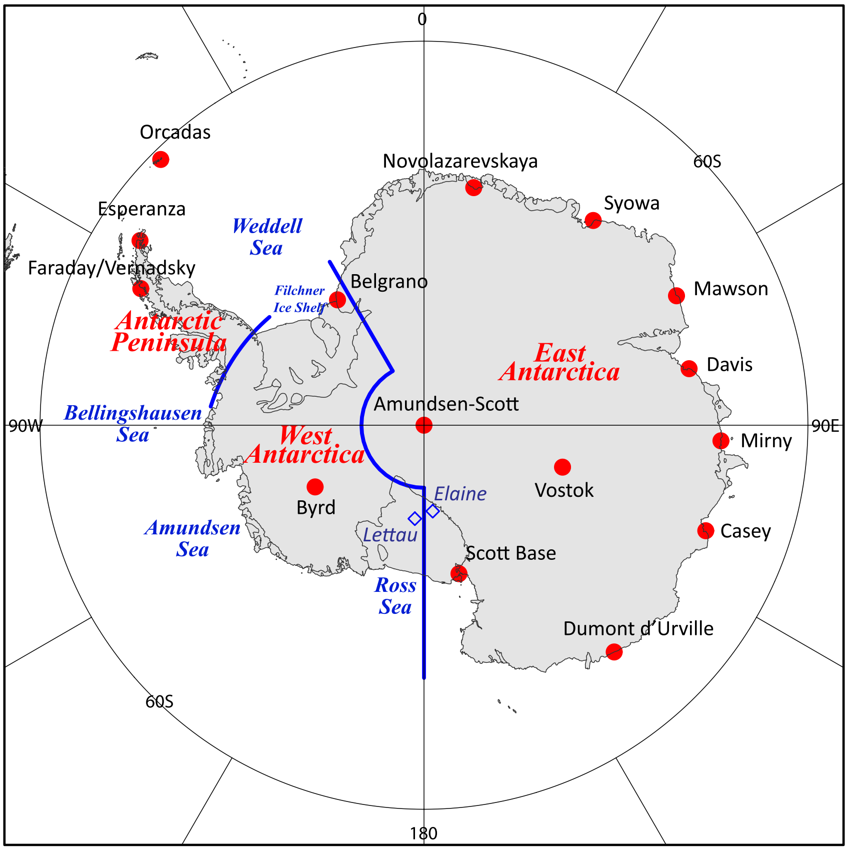

Figure 1. Long-term stations (red dots) used to reconstruct Antarctic surface temperatures at monthly intervals since 1958 (RECON). The regional sectors discussed here are outlined in blue: East Antarctica, West Antarctica, and the Antarctic Peninsula. Locations of automatic weather stations Lettau and Elaine on the southern Ross Ice Shelf are shown.

3. Results

Figure 2 compares the linear trends for ERA5 in comparison to RECON for 1958–2022, annually and seasonally. The ERA5 trends are larger than RECON that is based on observations and in particular ERA5 trend hotspots are present near 0° at the coast, over the Filchner Ice Shelf, and adjacent to the eastern side of the Ross Ice Shelf. The hotspots are present throughout the year but are more easily identified in the December–January–February (DJF) and MAM plots. There is little evidence from RECON to support these features. Figure 3 is the same as Figure 2 but for 1979–2022 when there are abundant satellite observations to constrain the reanalysis especially over the Southern Ocean and increasing numbers of observations on the continent (Lazzara et al., 2012). The ERA5 trend hotspots are equally prominent as for 1958–2022 (identified in Figure 3a) and most marked for DJF and MAM. The Antarctic warming trend in ERA5 for 1979–2022 is significantly larger than for RECON with the greatest differences occurring in DJF and JJA.

To check the ERA5 assimilation of 2-m air temperature, Figure 4 compares the station annual temperature anomaly time series used to construct RECON and the ERA5 values interpolated to the station locations for 1958–2022. A mixed picture emerges. For the Antarctic Peninsula stations of Faraday/Vernadsky, Esperanza, and Orcadas, ERA5 trends fit the station values closely, consistent with the validation analysis of González-Herrero et al. (2022). After 1979, the interannual variability in both observations and ERA5 agree at the three stations. For the interior stations of Byrd, Amundsen-Scott (South Pole), and Vostok, the ERA5 and station trends agree. There is some divergence between the time series prior to 1979. For the coastal stations of Belgrano, Novolazarevskaya, Mawson, Davis, Casey, Dumont d'Urville, and Scott Base, the ERA5 trends are much larger/larger than those observed. The time series for Mawson, Davis, Casey, Dumont d'Urville, and Scott Base converge around 1979 so that the observed and ERA5 trends and variability after 1979 are very similar. By contrast, the rapidly increasing ERA5 temperatures continue through 2022 for Belgrano and Novolazarevskaya unlike the observations. This result confirms the

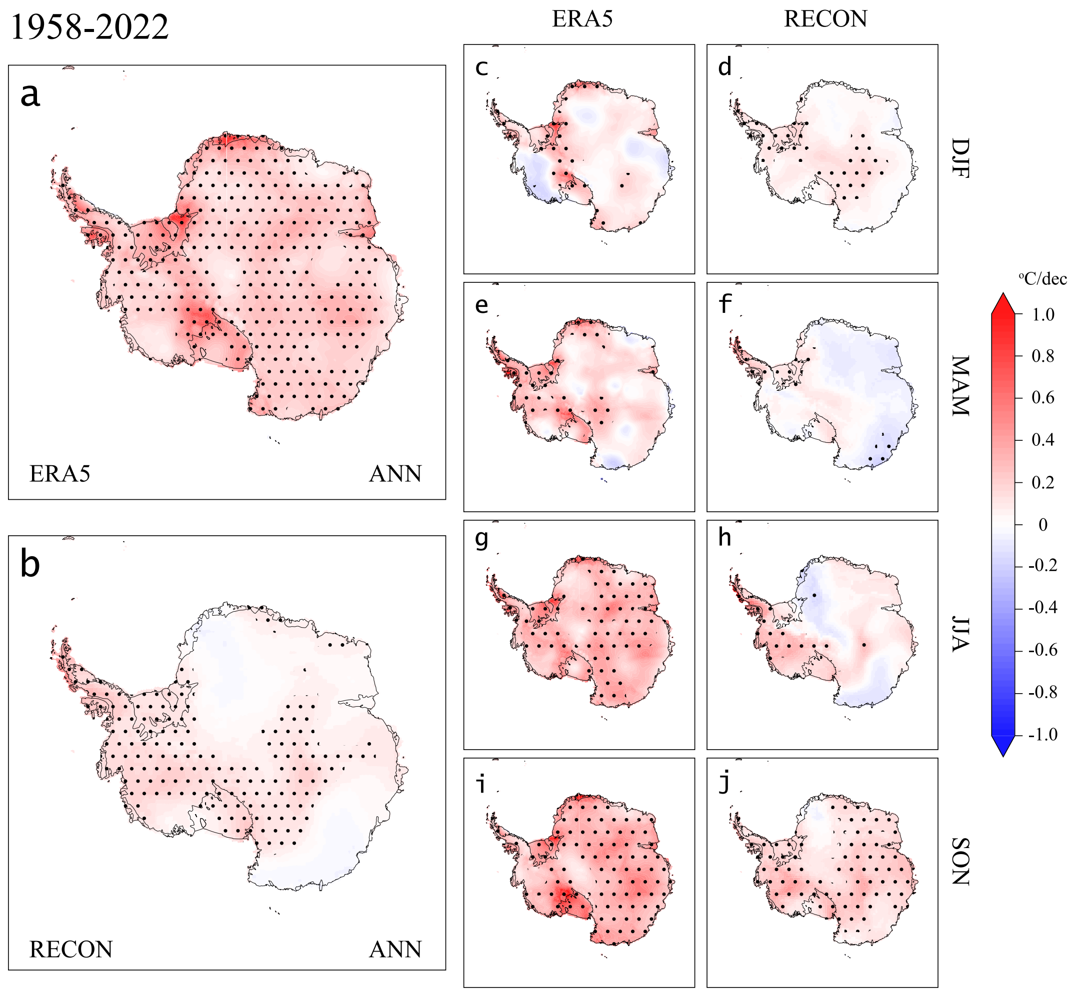

Figure 2. Spatial trends from both ERA5 and RECON for 1958–2022, annually (a, b) and by season (c, e, g, i, and d, f, h, j, respectively). The dots indicate statistical significance at the 0.01 level of the linear trends after considering the lag-1 autocorrelation after Santer et al. (2000).

anomalous long-term and recent ERA5 trend hotspots near these locations found by examining RECON. The trend hotspot near the southeastern Ross Ice Shelf cannot be definitively tested because there are no long-term stations in that vicinity. However, Lettau and Elaine automatic weather stations (AWS) observations are available from 1986 to 2022 and 1993–2022, respectively, but the records are comparatively short, and variability is high making trend differences not distinguishable statistically. Lettau data from the flat Ross Ice Shelf are consistent with ERA5 warming faster than observed at that location, with RECON matching the observations (Figure S1 in Supporting Information S1). Much closer to the steep Transantarctic Mountains, ERA5 captures the warming at Elaine better than RECON; this might be related much coarser 60-km resolution of RECON compared to the 31-km resolution of ERA5. With little warming observed at Lettau and marked warming at Elaine, the observations favor the spatial trend depiction of RECON on the southeastern Ross Ice Shelf rather than ERA5 (Figure 3). It is notable that ERA-Interim had warming hotspots in the same three locations discussed here (Nicolas & Bromwich, 2014, Figures 7e and 7f), all of which were concluded to be artifacts. Scattered among the faster temperature rise locations for ERA5 along the coast are those at Syowa, and Mirny where the trends are similar.

When the temperature trends are regionally averaged for the Antarctic Peninsula, West Antarctica, East Antarctica, and the entire continent (Table 1), the annual trends for ERA5 are all much larger than for RECON for 1958–2022 but much less so for 1979–2022. The contrast is not as marked for the Antarctic Peninsula which featured trends at the stations that were similar to each other (Figure 4). Further, the ERA5 trends are not always

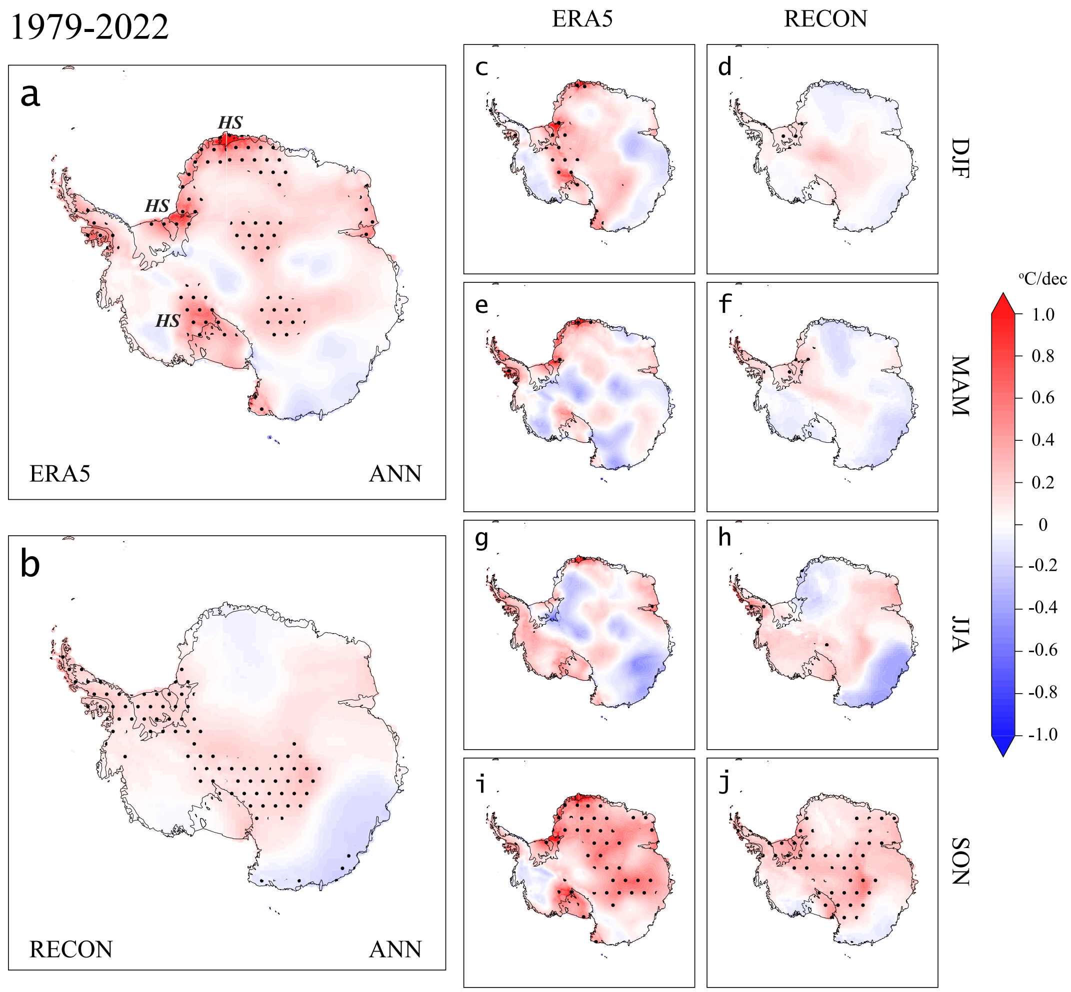

Figure 3. Spatial linear temperature trends from both ERA5 and RECON for 1979–2022, annually (a, b) and by season (c, e, g, i, and d, f, h, j, respectively). Stippling shows statistical significance at the p-value <0.01 level. HS locates the spurious trend hotspots discussed here.

statistically larger than RECON because the uncertainty of ERA5 is larger. The trend contrast is present for all seasons for 1958–2022 but is most different for MAM. The trend contrast is reduced for 1979–2022 with MAM and JJA trends being very similar. Finally, we provide the regional ERA5 temperature trends for 1940–2022 (not available for RECON) and they are close to those for 1958–2022, both annually and seasonally, because the latter period dominates the result, and 1940–1957 period does not show the 3 hotspot features.

4. Discussion

ERA5 temperature trends prior to 1979 are anomalous at many but not all coastal locations, being dominated by the model state not by the observations. The anomalous time series converge around 1979, the start of the modern satellite era, and the trends and variability after that are very similar. Soci et al. (2024) show in their Figure 8 that the ERA5 forecast skill for the entire Southern Hemisphere, and Australia-New Zealand in particular, increases abruptly in 1979 reflecting much higher reanalysis skill when abundant satellite observations are assimilated. Artifacts in ERA5 temperature trends continue to the present day at 3 locations: the East Antarctic coast near 0° longitude, the Filchner Ice Shelf, and probably adjacent to the southeastern Ross Ice Shelf. Confirmation that these artifacts are tied to the station observations is provided by their presence only from 1958 onward once the station observations become available. Collectively the ERA5 issues combine to make the ERA5 temperature trends for all of Antarctica too large throughout the duration of the reanalysis, 1940–2022. The issue is still present after 1979 but with greatly reduced magnitude. The northern Antarctic Peninsula and interior Antarctica

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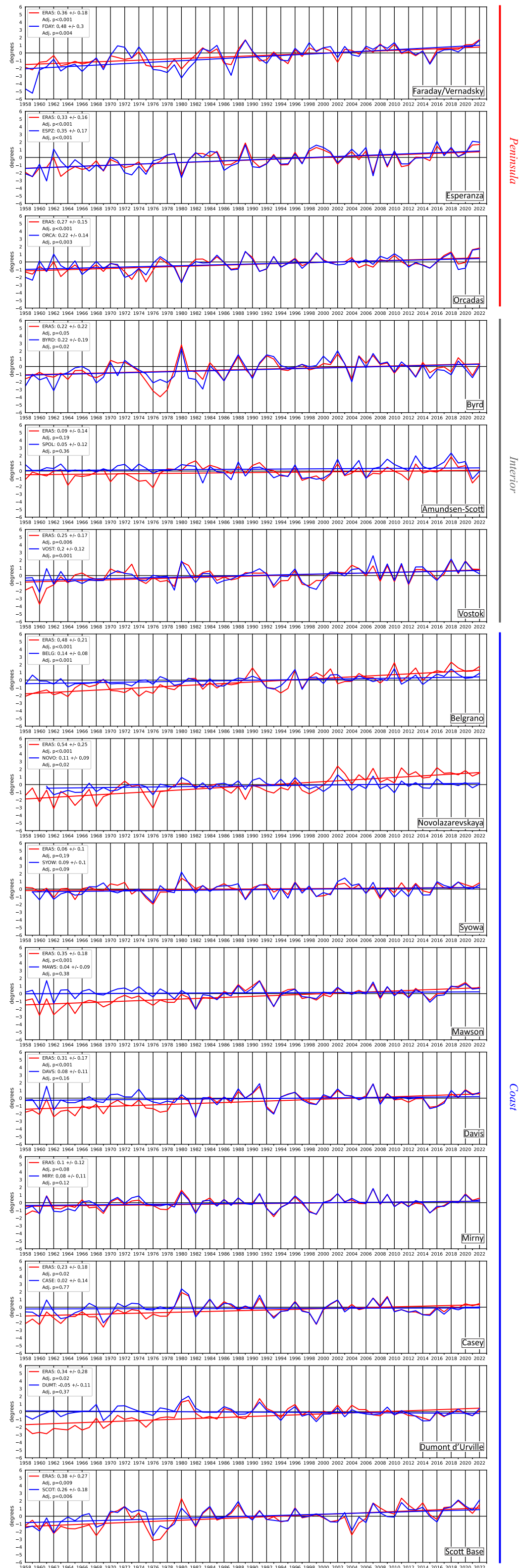

Figure 4. Annual temperature anomaly time series at long-term stations from observations versus ERA5 for 1958–2022 based on 1981–2010 climatology. Trends are for 1958–2022 in °C/decade with 99% confidence intervals. Adj. means that the p-value accounts for the impact of autocorrelation.

Table 1
Trends for ERA5 and RECON for East Antarctica, West Antarctica, the Antarctic Peninsula, and Continental Antarctica for 1958–2022 and 1979–2022

	ERA5			Reconstruction	
	1940–2022	1958–2022	1979–2022	1958–2022	1979–2022
	Annual			Annual	
East	0.20 ± 0.09	0.18 ± 0.12	0.06 ± 0.14	0.05 ± 0.05	0.04 ± 0.10
West	0.26 ± 0.15	0.34 ± 0.21	0.18 ± 0.15	0.12 ± 0.07	0.07 ± 0.09
Peninsula	0.38 ± 0.24	0.55 ± 0.31	0.38 ± 0.45	0.24 ± 0.12	0.21 ± 0.16
Continent	0.21 ± 0.10	0.21 ± 0.13	0.08 ± 0.12	0.07 ± 0.05	0.05 ± 0.08
	DJF			DJF	
East	0.14 ± 0.08	0.11 ± 0.12	0.21 ± 0.23	0.05 ± 0.08	0.02 ± 0.13
West	0.22 ± 0.09	0.21 ± 0.12	0.27 ± 0.17	0.07 ± 0.07	0.03 ± 0.09
Peninsula	0.09 ± 0.15	0.22 ± 0.25	−0.08 ± 0.36	0.11 ± 0.06	0.07 ± 0.08
Continent	0.16 ± 0.08	0.14 ± 0.11	0.22 ± 0.21	0.06 ± 0.06	0.02 ± 0.10
	MAM			MAM	
East	0.16 ± 0.12	0.13 ± 0.18	−0.11 ± 0.41	−0.03 ± 0.12	−0.03 ± 0.22
West	0.26 ± 0.16	0.29 ± 0.23	0.06 ± 0.27	0.04 ± 0.09	0.00 ± 0.17
Peninsula	0.38 ± 0.37	0.53 ± 0.48	0.65 ± 0.70	0.26 ± 0.17	0.21 ± 0.23
Continent	0.18 ± 0.12	0.17 ± 0.18	−0.07 ± 0.36	0.00 ± 0.10	−0.01 ± 0.18
	JJA			JJA	
East	0.29 ± 0.15	0.23 ± 0.20	−0.10 ± 0.24	0.03 ± 0.11	−0.01 ± 0.21
West	0.28 ± 0.17	0.36 ± 0.23	0.10 ± 0.29	0.17 ± 0.14	0.11 ± 0.24
Peninsula	0.72 ± 0.43	1.07 ± 0.62	0.58 ± 0.95	0.40 ± 0.22	0.30 ± 0.30
Continent	0.28 ± 0.14	0.26 ± 0.19	−0.06 ± 0.21	0.08 ± 0.10	0.04 ± 0.19
	SON			SON	
East	0.21 ± 0.14	0.24 ± 0.19	0.23 ± 0.27	0.15 ± 0.10	0.17 ± 0.14
West	0.29 ± 0.22	0.47 ± 0.25	0.28 ± 0.34	0.21 ± 0.12	0.14 ± 0.18
Peninsula	0.34 ± 0.26	0.36 ± 0.29	0.33 ± 0.53	0.20 ± 0.13	0.28 ± 0.24
Continent	0.23 ± 0.15	0.29 ± 0.21	0.24 ± 0.27	0.16 ± 0.09	0.17 ± 0.12
					(unit: °C/dec)

Note. 1940–2022 only provided and only providable for ERA5. Confidence intervals on the trends are 99%. Shaded values are statistically significant at the p-value <0.01 level.

are the regions where ERA5 has reasonably reliable trends for 1958–2022, with the former confirming the verification analysis of González-Herrero et al. (2022).

Why ERA5 contains spurious trend hotspots in the three low elevation regions cannot be easily determined from the present analysis, but the same hotspots were present in the ECMWF reanalysis that preceded ERA5, namely ERA-Interim (Nicolas & Bromwich, 2014; Zhu et al., 2021, Figure 9). A possible contributing factor for Novolazarevskaya and Belgrano Stations is that they could be present in ERA5 at hundreds of meters higher elevation than actual, and therefore several degrees warmer relative to the background field than actual. The temperature analysis may reject these observations because they differ from the background field by more than three times the combined observation and background errors. As the background field warms (see next paragraph), observation rejection becomes less likely. The elevation discrepancy argument is supported by the higher surface heights of the interpolated ERA5 locations used for these stations. By adiabatically adjusting ERA5 2-m temperatures from the interpolated ERA5 surface height to the station elevations, it was found that ERA5 annual cold biases for Novolazarevskaya were eliminated by 2022 but were still 2°C for Belgrano Station.

Figure 5 presents the ERA5 time series of Antarctic annual 2-m temperature departures for 1940–2022 period from the 1981–2010 ERA5 mean. It reveals the net effect of the issues identified here. There is an abrupt decrease

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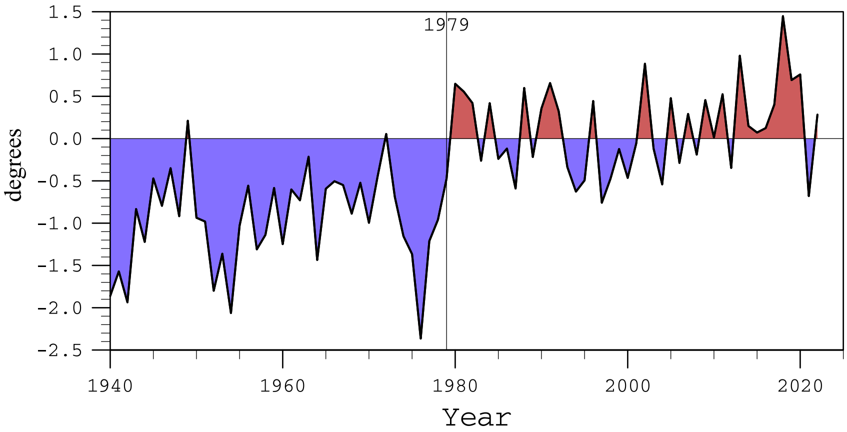

Figure 5. Annual 2-m air temperature departures over Antarctica (°C) from ERA5 in relation to the recent 30-year ERA5 climatology for 1981–2010.

in the annual negative values coinciding with the start of the modern satellite era in 1979. After 1979, the departures are reduced in magnitude and mixed in sign with a positive peak in 2018 corresponding to the warming described by Clem et al. (2020). This result suggests that the ERA5 model has a near-surface average annual cold bias of ∼1.0°C over Antarctica (maximizes in winter) that is mitigated once plentiful satellite observations are assimilated; similar behavior can be seen at many East Antarctic coastal stations in Figure 4. Determining the exact cold bias is complicated by the changing behavior around 1979 of the Southern Annular Mode with Antarctic temperatures (Marshall et al., 2022). Also, there appears to be two ERA5 temperature regimes prior to and post 1979 with most of the temperature trend from 1940 to 2022 being attributable to the temperature jump across the start of modern satellite era. This would mean that the long-term ERA5 temperature trends away from the stations examined here are dominated by the impact of satellite data assimilation.

It is concluded that ERA5 cannot be used for temperature climate change applications prior to 1979 but can be selectively applied for this purpose after 1979. Inspection of Figure 4 shows that ERA5 successfully captures the interannual variability at all station locations after 1979.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

ERA5 hourly data on single levels is available from ECMWF (Hersbach et al., 2023). Antarctic station and AWS near-surface air temperatures are available from the READER site maintained by British Antarctic Survey: https://www.bas.ac.uk/project/reader/#data (accessed on 30-May-2024). RECON data used in this study can be downloaded from Bromwich and Wang (2024).

Acknowledgments
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