

Evaluation of ERA5 and CARRA Reanalysis 2 m Air Temperature over Greenland Using Automatic Weather Station Observations

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Abstract. Accurate representation of near-surface air temperature over the Greenland Ice Sheet serves as the foundation for mass balance modelling and sea level projection. Due to sparse in-situ observations, reanalysis products have become an irreplaceable gridded temperature dataset. Using daily observations from automatic weather stations released by GEUS as the reference, this study systematically evaluates the performance of ECMWF ERA5 and CARRA in capturing daily 2-metre air temperature across the Greenland Ice Sheet for the full decade from 2016 to 2025. A total of 36 observation stations are involved in the comparison, with 110,104 matched triplet samples in total. The overall performance is further analysed at individual station, seasonal and interannual scales. The results show that CARRA achieves an overall RMSE of 1.70 °C and a correlation coefficient R of 0.991 across all samples, which is distinctly better than ERA5 with an RMSE of 3.76 °C and R of 0.952. CARRA outperforms ERA5 in terms of RMSE at 35 stations. It also presents much narrower distributions in station-wise metrics (median RMSE: 1.40 °C versus 3.14 °C) and seasonal metrics (peak-to-trough difference: 0.85 °C versus 2.13 °C). Winter witnesses the largest performance gap between the two datasets, with a difference of 2.73 °C in favour of CARRA. Neither product shows systematic accuracy drift from 2016 to 2024. The poorest performance of both products occurs at Scoresby Sound fjord in eastern Greenland (SCO_L/SCO_U), indicating that deep narrow fjords and steep coastal terrain pose challenges to both gridded datasets regardless of their spatial resolution. Even so, CARRA still holds a substantial advantage at these two sites, with RMSE values of 3.78 °C and 1.95 °C, compared with 9.23 °C and 7.60 °C for ERA5, which demonstrates the direct benefits brought by improved spatial resolution. This study provides references for selecting suitable datasets for applications relying on 2-metre air temperature, such as mass balance calculation and melt estimation based on positive degree days over the Greenland Ice Sheet. It is concluded that CARRA is currently the most reliable open-access gridded temperature product, while cautious use of ERA5 is recommended over fjord areas along the eastern coast and margins of the ablation zone.

Keywords: Greenland Ice Sheet, ERA5, CARRA, near-surface air temperature, automatic weather station

1. Introduction

The Greenland Ice Sheet stores freshwater ice equivalent to approximately 7.4 metres of global sea level rise. Changes in its surface mass balance (SMB) represent a major source of uncertainty for sea level projections in the 21st century. Near-surface air temperature drives summer melting through cumulative positive degree days and regulates annual heat exchange between snow, ice and the atmosphere via surface energy budgets, acting as a primary controlling factor of SMB. Therefore, accurate estimation of 2-metre air temperature is an essential input for ice sheet mass balance models and sea level prediction.

The Greenland Ice Sheet covers a complex terrain spanning plateaus, glaciers and coastal areas across about 2.4×10^6 km². The network of automatic weather stations (AWS) is relatively sparse and unevenly distributed. Most scientific and practical applications require gridded temperature fields with complete temporal coverage and continuous spatial distribution. Reanalysis products assimilate massive observational data, cover global or large regional domains, and extend datasets back for decades, making them irreplaceable gridded temperature sources. Among these, ERA5 (ECMWF Reanalysis v5) [1], produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), provides hourly atmospheric fields on a global 0.25° grid dating back to 1940. Thanks to its mature assimilation system and long time series, it has been widely adopted as a reference dataset for near-surface air temperature in global climate research. Targeted evaluations of ERA5 have also been conducted regarding surface meteorological parameters and turbulent fluxes in the seas around Greenland [2].

Nevertheless, even the most widely recognised state-of-the-art global reanalysis suffers from systematic limitations in simulating near-surface temperature over complex polar terrain. Its 0.25° grid cells in high-latitude Greenland cover anisotropic areas far larger than individual observation sites, failing to resolve near-surface temperature variations caused by steep coastal landforms, slope gradients across the ablation zone and sharp topographic fluctuations along ice sheet margins. To address this research gap, CARRA (Copernicus Arctic Regional Reanalysis) was first publicly released in 2021 under the funding of the Copernicus Climate Change Service (C3S) and led by MET Norway in collaboration with multiple Nordic meteorological and climate institutions [3, 4], [5]. Built on the non-hydrostatic mesoscale numerical weather prediction model HARMONIE-AROME and the three-dimensional variational (3D-Var) data assimilation system, CARRA delivers 3-hourly analysis outputs over the Arctic region including Greenland at a horizontal resolution of 2.5 kilometres. Its horizontal resolution is roughly an order of magnitude higher than that of ERA5, ranking it among the open-access reanalysis products with the finest resolution currently available for Greenland. As a relatively new dataset, CARRA still lacks systematic validation of near-surface air temperature accuracy across the full spatial extent of the Greenland Ice Sheet on seasonal and interannual timescales.

In terms of regional reanalysis assessment, reference [3] conducted a comparative evaluation of near-surface air temperature and wind speed between CARRA and ERA5 over CARRA-East, which covers Svalbard, the Barents Sea and northern Norway to Finland. The study confirmed that the advantages of CARRA over global reanalysis products mainly stem from its high resolution, which enables finer representation of terrain and land-sea boundaries. For evaluations of global reanalysis datasets on near-surface air temperature across Greenland, reference [6] systematically compared seven global reanalysis products, five gridded temperature datasets and multiple dynamical downscaling products at the monthly timescale. Using multi-source in-situ observations from PROMICE, GC-Net, DMI and other networks as benchmarks, the study illustrated discrepancies in

monthly temperature values and long-term trends of different products over the Greenland Ice Sheet. Reference [7] adopted observations from 36 stations covering 1996 to 2018 to compare five global reanalysis datasets including ERA5, ERA-Interim, MERRA-2, CFSR and JRA-55 on a monthly basis. It characterised the spatial patterns of warm biases in the accumulation zone and cold biases in the ablation zone, and quantified the relative accuracy of these products. Reference [8] used data from 21 stations in the PROMICE ablation zone from 2010 to 2016 to assess variable-wise performance of ERA5, ERA-Interim and other products at the daily timescale. The RMSE values of 2-metre air temperature in summer were 2.50 °C and 1.93 °C respectively, and the study explained the product discrepancies from the perspective of ice surface parameterisation schemes. The latest research [9] carried out a comprehensive assessment of ERA5, ERA5-Land, MERRA-2 and NCEP/DOE R2 at monthly, daily and hourly scales based on observations from 49 stations during 2018–2022, and verified that ERA5 and MERRA-2 outperformed other datasets across Greenland. However, this assessment only focused on global reanalysis products, excluding regional reanalysis datasets such as CARRA. Collectively, these studies have established standard methodologies and fundamental understandings for validating near-surface air temperature over Greenland. To date, however, few studies have performed systematic daily-scale comparison and validation of 2-metre air temperature between ERA5 and CARRA using the AWS network across the Greenland Ice Sheet.

Taking daily AWS observations compiled and released by GEUS as the ground truth, this study evaluates the accuracy of daily mean 2-metre air temperature from CARRA and ERA5 over a full ten-year period from 2016 to 2025. The overall performance is further analysed at individual station, seasonal and interannual levels. The rest of this paper is organised as follows. Section 2 describes three types of datasets, namely AWS, ERA5 and CARRA. Section 3 elaborates station selection, temporal and spatial matching methods and statistical metrics. Section 4 presents validation results regarding overall accuracy and performance decomposed into the three aforementioned dimensions. Section 5 summarises the main conclusions.

2. Data

2.1. Automatic weather station observations

This study adopts the combined dataset from three observation networks, namely PROMICE (Programme for Monitoring of the Greenland Ice Sheet), GC-Net (Greenland Climate Network) and GlacioBasis, compiled and released by GEUS (Geological Survey of Denmark and Greenland) as the validation benchmark. The data are retrieved from the GEUS Dataverse, and the Level 3 daily snapshot V37.0 is used [10–12]. The research period spans from 1 January 2016 to 31 December 2025. The original 10-minute readings are transmitted as hourly averages via the Iridium system and then aggregated into daily means. A total of 36 stations meet the screening criteria within the study period, and their spatial distribution is presented in Figure 1.

Air temperature is represented by the variable t_u , the arithmetic daily mean measured at the upper boom. It should be noted that t_u is not strictly 2-metre air temperature. The actual height above the ground is determined by the daily recorded z_{boom_u} , which constitutes an inherent uncertainty between AWS observations and reanalysis products. Sensor accuracy varies by model. The predominant Rotronic MP100H has a nominal accuracy of ± 0.1 K, while the Lufft WS401-UMB achieves ± 0.2 K at temperatures above -20 °C with reduced accuracy under cold conditions. The Vaisala HMP155 yields an accuracy of approximately ± 0.37 K at -50 °C. The overall noise floor is around 0.5 K, meaning product biases with absolute values below this threshold shall not be interpreted as credible signals.

Raw data have undergone quality control by GEUS, including spike removal, range threshold filtering and persistence filtering. Manual flags are also assigned to poor-quality periods caused by tilted masts, snow coverage and human interference. No additional quality control is conducted in this study.

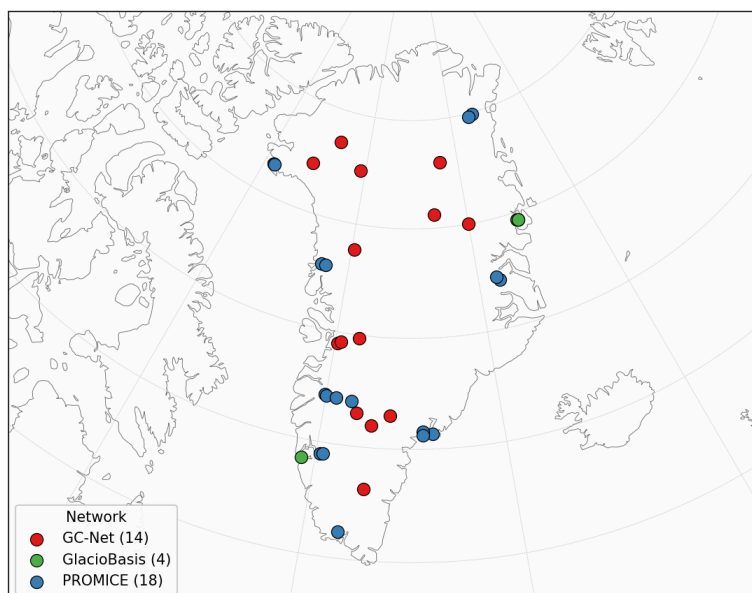


Figure 1. Spatial distribution of greenland AWS stations used in this study

2.2. ERA reanalysis

ERA5 is the flagship global atmospheric reanalysis product currently developed by ECMWF. It integrates conventional surface and upper-air observations, satellite radiances, as well as ocean and cryosphere observations using a 4D-Var (four-dimensional variational) data assimilation system. It provides hourly atmospheric fields on a 0.25° latitude-longitude grid with 137 vertical model layers, covering the period from 1940 to the present. The 2-metre air temperature variable of ERA5 is employed in this study, and grid values are matched to AWS stations via the nearest-neighbour method. Over the commonly studied latitudes of 60° – 80° N across Greenland, each 0.25° grid cell is approximately 28 km in zonal direction and 7–14 km in meridional direction, which is relatively coarse compared with the typical topographic scales of the ice sheet. The temporal data are instantaneous values at full UTC hours. There is a slight difference in sampling mode between these instantaneous values and the hourly averages aggregated from 10-minute AWS readings, yet the two are regarded as equivalent when converted to daily mean values in this research.

2.3. CARRA reanalysis

CARRA is the flagship Arctic regional reanalysis product funded by the Copernicus Climate Change Service and developed by MET Norway in collaboration with multiple Nordic meteorological and climatic institutions [3-5]. Its atmospheric component is built upon the non-hydrostatic mesoscale numerical weather prediction system HARMONIE-AROME. Atmospheric fields are produced through 3D-Var assimilation of conventional surface and upper-air observations, satellite radiances and local observational data from countries across the Arctic region. Surface variables including snow depth, soil temperature and soil moisture are assimilated by optimal interpolation, and physical

parameterisation schemes for cold underlying surfaces such as snow and ice are specially optimised. Driven by ERA5 analysis fields as lateral boundary conditions, the model outputs instantaneous 3-hourly analysis products at 65 vertical layers, rather than cumulative or averaged values. This study uses the 2-metre air temperature from the CARRA-West domain covering Greenland, Iceland and surrounding areas, with nearest-neighbour matching applied for AWS stations. The dataset adopts a Lambert conformal projection with a horizontal grid resolution of $2.5 \text{ km} \times 2.5 \text{ km}$. Its meridional resolution is roughly 11 times finer than that of ERA5, and the zonal resolution at high latitudes of Greenland is about 3 to 6 times higher.

3. Methods

3.1. Temporal and spatial matching

Spatially, each AWS station is matched to the nearest grid centre of the reanalysis products. Time series are extracted on a single-point basis rather than geographic subset slicing to facilitate direct pairwise comparison. For the regular latitude-longitude grid of ERA5 with a resolution of 0.25° , the grid centre with the closest coordinates is selected directly. For the Lambert 2D grid of CARRA, the nearest neighbour is identified via haversine distance calculation within the two-dimensional grid index space. Temporally, all three datasets are aligned according to UTC calendar dates. The AWS data have been pre-aggregated by GEUS. The hourly series of ERA5 and 3-hourly series of CARRA are resampled into daily mean values based on UTC time. The final matched dataset contains a total of $N=110104$ paired samples.

3.2. Statistical metrics

Let P_i denote the daily mean 2-metre air temperature of the evaluated product (ERA5 or CARRA) for the i -th paired sample, and O_i represent the corresponding daily mean observation from AWS. N is the total number of paired samples included in the statistics. Four standard metrics are adopted to quantify the agreement between reanalysis products and observations, namely bias, mean absolute error (MAE), root mean square error (RMSE) and Pearson correlation coefficient R .

$$\text{Bias} = \frac{1}{N} \sum_{i=1}^N (P_i - O_i), \quad (1)$$

$$\text{MAE} = \frac{1}{N} \sum_{i=1}^N |P_i - O_i|, \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (P_i - O_i)^2}, \quad (3)$$

$$R = \frac{\sum_{i=1}^N (P_i - \bar{P})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^N (P_i - \bar{P})^2 \sum_{i=1}^N (O_i - \bar{O})^2}} \quad (4)$$

where P and O are the arithmetic means of product values and observational values across all N samples, respectively. Bias reflects systematic deviation, and a positive value indicates warm bias of the product. MAE and RMSE describe the overall magnitude of errors, while RMSE is more sensitive to large deviations. The correlation coefficient R measures the synchronisation of daily variations between reanalysis outputs and in-situ observations.

4. Results

4.1. Overall accuracy

Over the entire validation period from 2016 to 2025 (N = 110104), CARRA outperforms ERA5 remarkably in terms of RMSE, MAE and correlation coefficient (Figure 2). The RMSE drops from 3.76 °C for ERA5 to 1.70 °C for CARRA, representing a reduction of approximately 55%. The MAE decreases from 2.82 °C to 1.15 °C. The correlation coefficient R rises from 0.952 to 0.991, and the corresponding explained variance increases from roughly 91% to 98%. The overall bias of both products is close to zero ($|\text{"bias"}| < 0.10 \text{ }^{\circ}\text{C}$). Nevertheless, this near-zero total bias results from the mutual offset of deviations across individual samples. Further analysis is conducted by decomposing the results at station, seasonal and interannual scales in the following sections.

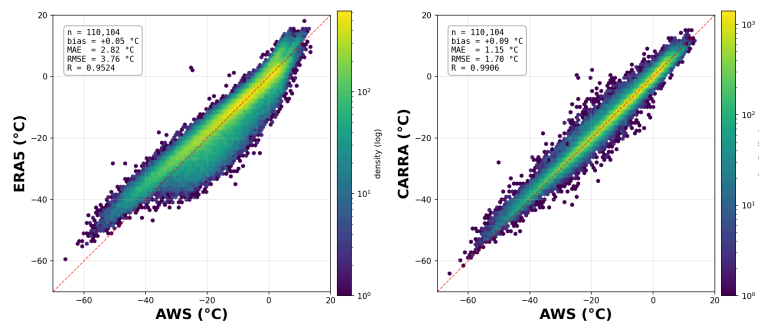


Figure 2. Density scatter plots of daily mean 2-metre air temperature from ERA5 (left) and CARRA (right) against AWS observations. The red dashed line denotes the 1:1 reference line

4.2. Inter-station differences

Figure 3 presents the RMSE of daily mean 2-metre air temperature for each of the 36 stations, sorted in descending order of ERA5 RMSE values. Figure 4 shows the spatial distribution of RMSE. ERA5 exhibits large performance disparities among stations, with a median RMSE of 3.14 °C and a range from 2.08 °C (UPE_U) to 9.23 °C (SCO_L). In contrast, CARRA has a much narrower value distribution, with a median RMSE of 1.40 °C and a range from 0.89 °C (JAR) to 3.78 °C (SCO_L). Station-wise comparison indicates that CARRA achieves better results than ERA5 at 35 out of 36 stations. The only exception is the NSE station, where ERA5 (3.07 °C) performs slightly better than CARRA (3.26 °C). The poorest performance of both products occurs at SCO_L and SCO_U, located deep inside the Scoresby Sound fjord in eastern Greenland. The RMSE values of ERA5 are 9.23 °C and 7.60 °C, while those of CARRA are 3.78 °C and 1.95 °C respectively. The complex terrain consisting of narrow deep fjords and steep coasts poses challenges to reanalysis products with both grid resolutions. The 0.25° grid (approximately 28 km) of ERA5 fails to resolve such fine terrain features effectively. Benefiting from the 2.5 km grid, CARRA reduces the RMSE by about 5 °C in this region, which demonstrates the most prominent improvement brought by higher spatial resolution.

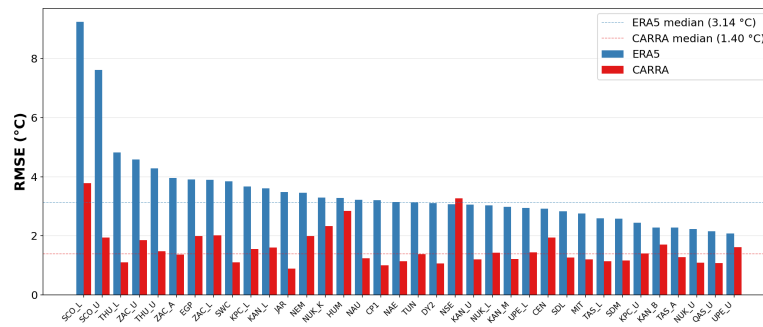


Figure 3. RMSE of daily mean 2-metre air temperature at each station for ERA5 (blue) and CARRA (red). Dashed lines represent the median RMSE of the 36 stations for each product

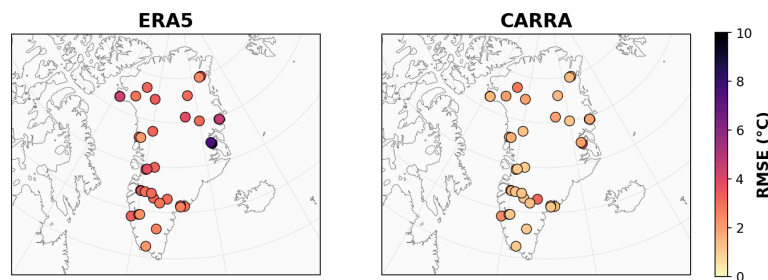


Figure 4. Spatial distribution of RMSE of daily mean 2-metre air temperature at AWS stations for ERA5 (left) and CARRA (right)

4.3. Seasonal differences

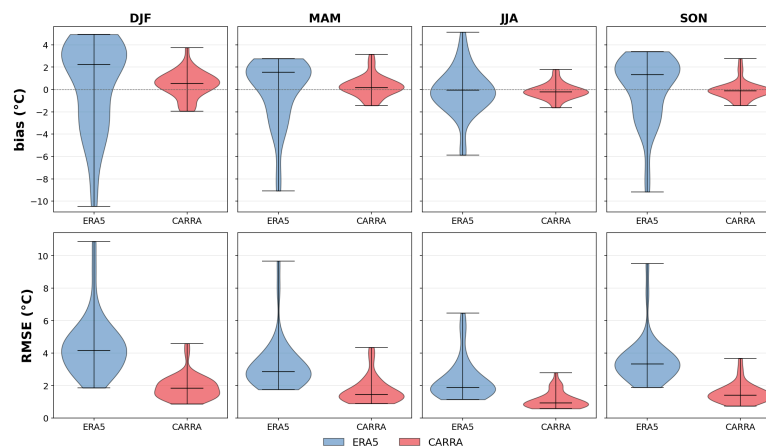


Figure 5. Distributions of bias (upper panel) and RMSE (lower panel) of ERA5 and CARRA across 36 stations for each season

The RMSE of both products shows a distinct seasonal cycle, with the poorest performance in winter (DJF) and the best in summer (JJA) (Figure 5). The RMSE of ERA5 decreases from 4.80 °C in winter to 2.67 °C in summer, with a peak-to-trough difference of approximately 2.13 °C. Meanwhile, the RMSE of CARRA declines from 2.07 °C to 1.22 °C, with a peak-to-trough difference of only 0.85 °C. This indicates that CARRA features not only higher overall accuracy but also better stability across seasons. The bias of both products remains close to zero in all seasons

($|\text{bias}| < 0.5\text{ }^{\circ}\text{C}$), with no notable seasonal systematic deviation. The maximum RMSE in winter is physically attributed to strongly stable boundary layers, near-surface temperature inversions and longwave radiative cooling over snow surfaces during the polar night. These processes are highly sensitive to grid resolution. The 0.25° grid of ERA5 fails to resolve such features effectively, while the 2.5 km grid of CARRA can well capture them at the station scale. Accordingly, winter sees the largest absolute advantage of CARRA over ERA5, with an RMSE gap of $2.73\text{ }^{\circ}\text{C}$, compared with $1.45\text{ }^{\circ}\text{C}$ in summer.

4.4. Interannual variability

The RMSE of the two products remains highly stable from 2016 to 2024 (Figure 6). The RMSE of ERA5 ranges from $3.72\text{ }^{\circ}\text{C}$ to $4.01\text{ }^{\circ}\text{C}$, and that of CARRA fluctuates between $1.54\text{ }^{\circ}\text{C}$ and $1.95\text{ }^{\circ}\text{C}$, with no obvious long-term trends over the decade. The year 2019 records the highest RMSE for both products, at $4.01\text{ }^{\circ}\text{C}$ for ERA5 and $1.95\text{ }^{\circ}\text{C}$ for CARRA. This year witnessed the most anomalous melting season of the Greenland Ice Sheet between 1948 and 2019, dominated by an unprecedented number of days with the Greenland blocking high and persistent anticyclonic circulation, accompanied by massive incursions of warm and moist air [13]. Such conditions led to substantial deviations of atmospheric profiles and surface energy budgets from normal states, posing greater challenges to reanalysis datasets. The RMSE values in 2025 are markedly lower than those in other years, at $3.03\text{ }^{\circ}\text{C}$ for ERA5 and $1.21\text{ }^{\circ}\text{C}$ for CARRA. However, the number of valid samples in 2025 drops by roughly 17% relative to the period 2016–2019, so this discrepancy cannot be regarded as evidence of actual changes in product accuracy. Overall, neither reanalysis product exhibits systematic accuracy drift throughout the ten-year validation period.

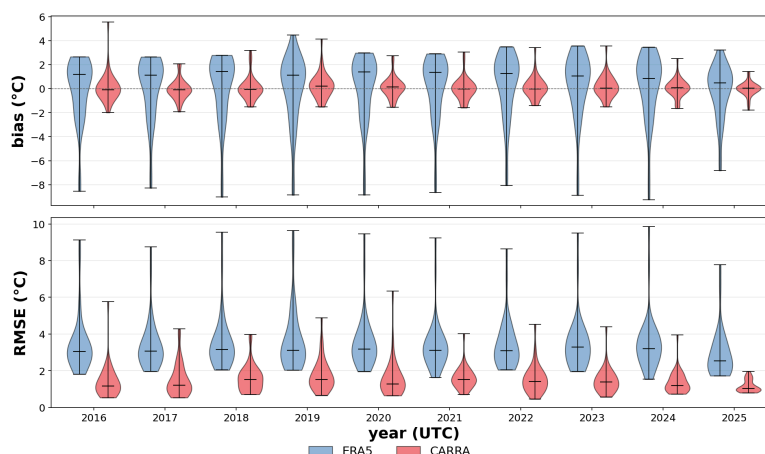


Figure 6. Annual distributions of bias (upper panel) and RMSE (lower panel) of ERA5 and CARRA across 36 stations

5. Conclusions

Based on observations from 36 stations of PROMICE, GC-Net and GlacioBasis across Greenland, this study systematically validates the daily mean 2-metre air temperature derived from CARRA and ERA5 over the full ten-year period from 2016 to 2025 ($N=110104$). The main conclusions are summarised as follows.

In terms of overall accuracy, CARRA outperforms ERA5 significantly. Its RMSE decreases from $3.76\text{ }^{\circ}\text{C}$ to $1.70\text{ }^{\circ}\text{C}$, a reduction of around 55%. The MAE falls from $2.82\text{ }^{\circ}\text{C}$ to $1.15\text{ }^{\circ}\text{C}$, and the

Pearson correlation coefficient rises from 0.952 to 0.991. The overall bias of both products across all samples is close to zero ($|\text{bias}| < 0.10\text{ }^{\circ}\text{C}$).

At the station scale, CARRA yields lower RMSE values than ERA5 at 35 out of 36 stations, with NSE being the only exception. The median RMSE is $1.40\text{ }^{\circ}\text{C}$ for CARRA versus $3.14\text{ }^{\circ}\text{C}$ for ERA5. The RMSE distribution among stations is much narrower for CARRA, ranging from $0.89\text{ }^{\circ}\text{C}$ to $3.78\text{ }^{\circ}\text{C}$, while the range for ERA5 is $2.08\text{ }^{\circ}\text{C}$ to $9.23\text{ }^{\circ}\text{C}$. The worst performance of both products occurs at SCO_L and SCO_U located deep within the Scoresby Sound fjord in eastern Greenland, demonstrating that deep narrow fjords and steep coastal terrain create difficulties for datasets of both grid resolutions. Even so, the RMSE of CARRA at these two sites ($3.78\text{ }^{\circ}\text{C}$ and $1.95\text{ }^{\circ}\text{C}$) is approximately $5\text{ }^{\circ}\text{C}$ lower than that of ERA5 ($9.23\text{ }^{\circ}\text{C}$ and $7.60\text{ }^{\circ}\text{C}$). The advantages of the 2.5 km grid in resolving steep coastal topography are most prominent in this area.

CARRA also presents better stability than ERA5 on seasonal and interannual timescales. Both products perform worst in DJF and best in JJA, yet the seasonal peak-to-trough RMSE difference of CARRA ($0.85\text{ }^{\circ}\text{C}$) is far smaller than that of ERA5 ($2.13\text{ }^{\circ}\text{C}$). The superiority of CARRA is most pronounced in winter, with an RMSE gap of $2.73\text{ }^{\circ}\text{C}$, compared with $1.45\text{ }^{\circ}\text{C}$ in summer. From 2016 to 2024, the RMSE of ERA5 stays between $3.72\text{ }^{\circ}\text{C}$ and $4.01\text{ }^{\circ}\text{C}$, and that of CARRA ranges from $1.54\text{ }^{\circ}\text{C}$ to $1.95\text{ }^{\circ}\text{C}$, with no systematic accuracy drift for either dataset. The extreme melting year of 2019 corresponds to the poorest performance of ERA5.

For practical applications, CARRA can serve as the most reliable gridded air temperature dataset for Greenland at present, while the applicability of ERA5 varies greatly across regions. For research relying heavily on 2-metre air temperature, such as Greenland Ice Sheet mass balance modelling, surface energy budget analysis and positive degree-day melt estimation, CARRA is the preferred choice. ERA5 remains applicable over the interior ice sheet, but adopting a single grid point to represent station-scale conditions in fjords along the eastern coast and at the margins of the ablation zone will introduce systematic biases of several degrees Celsius.

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