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Brief communication: Significant cold bias in ERA5 output for McMurdo Dry Valleys region, Antarctica

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Abstract. The ERA5 climate reanalysis dataset plays an important role in applications such as monitoring and modelling climate system changes in polar regions. Hence, the calibration of the reanalysis to ground observations is of great relevance. Here, we compare the 2-metre air temperature time series of the ERA5 reanalysis to the near-ground air temperature measured in 17 Automatic Weather Stations in the McMurdo Dry Valleys, Antarctica. We find that the reanalysis data has at best, a systematic cold bias of ~ 2°C. Our results show that future work should rely on secondary observations to calibrate when using the ERA5 reanalysis in polar regions.

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Short Summary. By analyzing temperature time series over more than 20 years, we have found a discrepancy between the 2-metre temperature values reported by the ERA5 reanalysis and the Automatic Weather Stations in the McMurdo Dry Valleys, Antarctica. The ERA5 reanalysis temperatures are systematically colder by ~2°C.

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1 Introduction

ERA5 dataset represents the fifth iteration of ECMWF (European Center for Medium-Range Weather Forecasts) global climate hindcasting based on the Integrated Forecasting System (IFS) Cy41r2 derived by a combination of data assimilation and short-term simulations applying an operational numerical weather prediction (NWP) model (Hersbach et al, 2020). With its global coverage, high temporal resolution, and relatively high spatial resolution of 31 km this dataset may prove particularly useful for research in polar regions such as Antarctica, where long-term climate observations are geographically sparse and often temporally discontinuous (Lazzara et al, 2012). A recent study found encouraging agreement between ERA5 output and AWS (Automatic Weather Station) data from 13 stations located in the southern section of

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Antarctic Peninsula (Tetzner et al., 2019). However, at least one other study has pointed out differences between ERA5 and selected weather stations across all Antarctica (Zhu et al., 2021).

Here, we report the results of a regional comparison between monthly 2-metre air temperatures in the McMurdo Dry Valleys region, Antarctica, reported in the ERA5 dataset and corresponding observations from 17 AWS locations. We focus our analysis on this region because of the relatively high spatial and temporal coverage of AWS observations and due to the high multidisciplinary research interest in this region which contains the main USA and New Zealand research stations and is proximal to Italian and Korean research stations. Despite the encouraging results found by Tetzner et al. (2019) for the southern Antarctic Peninsula, we find a significant cold bias in the near-surface air temperatures measured at the AWS and the temperatures reported in the reanalyses datasets.

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2. Data and methods

We analyze the daily surface temperature (2-metre temperature) recorded at 17 AWS (Figure 1) managed by the McMurdo Dry Valleys Long Term Ecological Research Project (LTER) since 1992, although some of the stations have been reporting data only since 1986 (Doran et al., 2002). We compare the AWS data to the monthly ECMWF ERA5 climate reanalysis surface temperature data (Muñoz Sabater, 2019) and we also we tested against the near-surface bias-corrected reanalysis dataset (BCR) (Cucchi et al., 2022). The latter is obtained from applying the Water and Global Change (WATCH) forcing data methodology (Weedon et al., 2010) to the ERA5 dataset, which includes interpolating to a 0.5° × 0.5° grid and using an elevation and other monthly-based biases corrections (Weedon et al., 2011, 2014; Cucchi et al., 2022). For each LTER AWS, where daily 2-metre air temperature data was available, we ran a 30-day moving average filter with no overlap to obtain monthly time series. The ERA5 and BCR grid nodes used to compare to each individual AWS were selected by minimizing the haversine distance between each AWS and all the nodes in the reanalysis grid. Finally, we interpolated both time series to a regular monthly sequence and the time series for the ERA5 node data were truncated to match the periods where data was available at their corresponding

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AWS. The elevation of the AWS and the nearest ERA5/BCR grid cells are often different, which can induce differences in the measured and calculated values of 2-metre air temperature. Therefore, we correct for the difference in altitude by applying an environmental lapse rate of 6.5 °C/km to the ERA5/BCR data (see also Weedon et al., 2010; Zhu et al., 2021). We report the mean temperature for the span of each time series and the standard error of the mean for each sample for the differences between the ERA5 and BCR datasets and the AWS with and without the altitude correction.

Furthermore, we compare the two data sets by analyzing the correlograms of the altitude corrected temperatures and performing a linear regression. Figure 2.b shows an example of this comparison. We report the squared correlation coefficients (R^2) as a metric of the goodness of fit and the p-values from the F-statistic to assess the level of statistical significance.

3. Results

Table 1 summarizes the AWS used in this study and table 2 show the results of our comparison. Both the ERA5 and BCR datasets show a cold bias compared to the AWS temperatures. Overall, the ERA5 dataset shows a smaller bias than the BCR dataset. The altitude correction applied to the grid temperatures does not eliminate but reduces the average bias across all stations. However, this is not the case for all stations; for ERA5, the altitude correction increases the bias at two stations (FRSM and UHDM), and for BCR the correction increases the bias at four stations (BENM, BRHM, CAAM and FLMM). Furthermore, even though the largest difference in the mean between the AWS station and the closest ERA5 grid node is observed for a station at high altitude (BENM, Beacon Valley), the results do not show a clear correlation between bias and elevation. On the other hand, our results do show some correlation between bias and latitude, with the southernmost stations showing a larger cold bias and the stations to the north a reduced cold bias and even a positive bias for the northernmost station (VIAM, Lake Vida).

Figure 2 illustrates the comparison of AWS and ERA5 monthly temperature time series for one of 17 locations used in this study (Lake Hoare) over the time span of two decades. The monthly temperature

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Deleted: there are other stations at relatively high altitudes that report a smaller bias (e.g., Friis Hills) and conversely, the Taylor Valley AWS station is not at a high altitude, but it does report a significant bias. The only station where the ERA5 average temperature was warmer than the corresponding AWS was located at Lake Vida, in Wright Valley.

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Table 1. List of available AWS in the McMurdo Dry Valleys region and comparison to ERA5 closest node.

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mismatch is particularly large during the summer months, even after applying the lapse-rate correction, when observations indicate actual temperatures were up to +5°C higher than ERA5 temperatures (Figure 2c) and up to +15°C than the BCR temperatures (Figure 2d). This observation can be seen for almost all stations, suggesting that the greatest source of the differences in average temperatures is the biases during the summer. Figure 2c,d suggests that there is a strong seasonality in the relationship between the data sets. During the austral Winter and Summer seasons the temperatures are generally closely clustered together, systematically being closer correlated during the Winter and more dispersed during the Summer. The Spring and Fall seasons show a hysteresis that is repeated over all the comparisons. As the environment warms up during the Spring months the ERA5 and BCR temperatures are above the best-fit line and drop below it during the Fall. These seasonal biases may ultimately be helpful in revealing what climate processes must be better represented in the ERA5 reanalysis to eliminate the strong observed temperature bias.

4. Discussion

Our results differ significantly from the findings reported by Tetzner et al. (2019) for the Southern Antarctic Peninsula - Ellsworth Land region. For that region there is a slight cold bias of the ERA5 surface temperatures close to the coast (-0.51°C ± 0.74) and a slight warm bias in the mountain range escarpment (+0.14°C ± 0.72) which has encouraging implications for using the reanalysis data where there is no AWS coverage, which represents most of Antarctica. In contrast, we find no clear topographic dependence on the temperature differences between AWS and ERA5 data, even though the largest difference is indeed in a high-altitude station, yet not the highest station. The magnitude of the overall cold bias (average of all differences) for the ERA5 dataset is 5.5 ± 0.8 °C and 2.1 ± 0.7 °C without and with the lapse-rate correction, respectively. For the BCR data, the cold biases are much greater, 10.2 ± 0.7 °C and 6.4 ± 1.3 °C for the data without the altitude correction and with the altitude correction, respectively. These values are about an order of magnitude larger as compared to the study of Tetzner et al. (2019). The largest cold biases for the altitude-

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corrected ERA5 and BCR data are observed during the summer months with average differences of 3.3 ± 0.1 °C and 7.2 ± 0.3 °C, respectively. This may be a particularly significant problem given the fact that warm summer temperatures determine the annual melt rate of snow, glaciers, and permafrost in Antarctica. Modelling of snow or ice melting driven by ERA5 temperatures (e.g., Costi et al., 2018) with a strong cold bias, as observed in our study region, will result in a significant underestimate of summer melt production. In general, our results agree with the findings of Zhu et al. (2021) in that they also find a cold bias for West Antarctica. However, our results highlight the degree in which such biases can be found at a regional and local scale and by using different datasets. Although the ERA5 reanalysis and its bias-corrected version are outstanding sources of global climate variables, the discrepancy between our results and those obtained by Tetzner et al. (2019) suggests that secondary observations should be used to test the reliability of the ERA5 and BCR dataset in polar regions, particularly when performing studies at scales shorter than 0.5°.

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5. Conclusions

We have compared the surface temperature (2-metre temperature) recorded at 17 AWS in the McMurdo Dry Valleys, Antarctica with temperatures from the ERA5 reanalysis dataset. We found that the temperatures reported by the global climate reanalysis and its bias-correction version are, on average, 2.1 ± 0.7 °C and 6.4 ± 1.3 °C colder than the temperatures recorded at the permanent weather stations. The cold temperature bias appears to be the largest during the warm summer months (3.3 ± 0.1 °C and 7.2 ± 0.3 °C), when loss of snow and ice to melting is the largest. We advise using secondary observations to assess the accuracy of parameters included in ERA5 reanalysis for polar regions.

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Acknowledgements. The maps shown in this work were made using The Generic Mapping Tools (GMT)(Wessel et al., 2019). The Landsat imagery used is from the Landsat Image Mosaic Of Antarctica (LIMA) project (Bindschadler et al., 2008) and can be accessed at https://lima.usgs.gov/index.php. This material is based upon work supported by the National Science Foundation under grant no. 1644187 to S. Tulaczyk.

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Data availability. The AWS data were provided by the NSF-supported McMurdo Dry Valleys Long Term Ecological Research program (OPP-1637708) and can be accessed at:

https://mcm.lternet.edu/meteorological-stations-location-map. The "ERA5-Land hourly data from 1950 to present" (DOI: 10.24381/cds.e2161bac) and the "Near surface meteorological variables from 1979 to 2019 derived from bias-corrected reanalysis" (DOI: 10.24381/cds.20d54e34) were downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store.

Author contributions. ST conceived the study. RGG performed the analysis. RGG and ST prepared the manuscript with equal contributions.

Competing interests. The authors declare that they have no conflict of interest.

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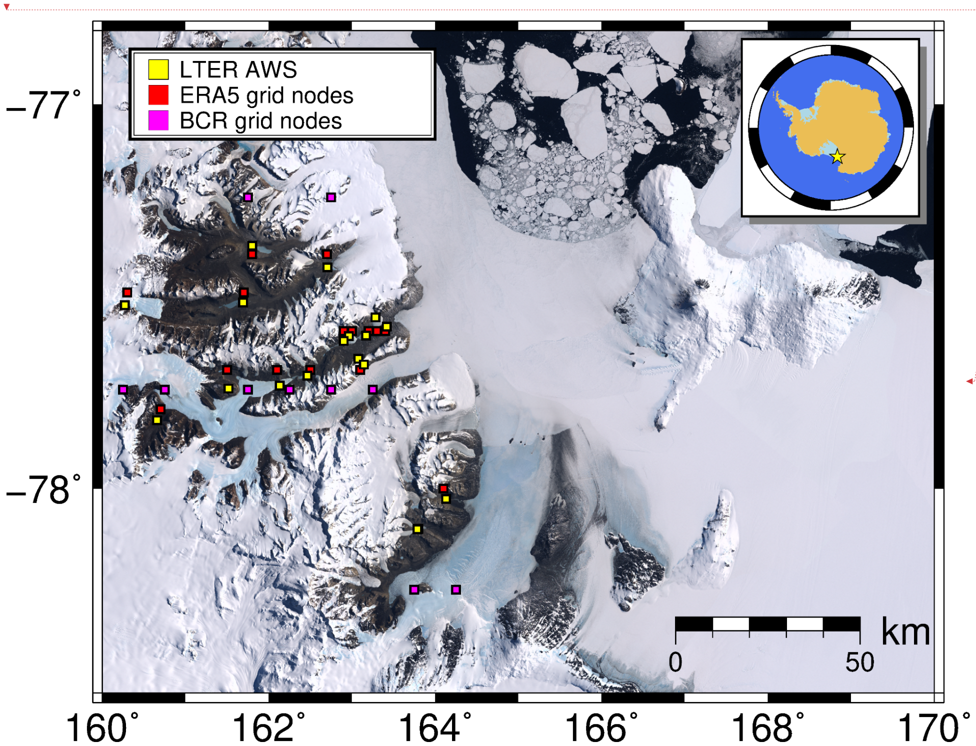

Figure 1. Map of the McMurdo Dry Valleys region. The location of the AWS managed by LTER is displayed with yellow squares and their corresponding closest ERA5 and BCR grid nodes with red and

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magenta squares, respectively. The distance to the sea and the topography of the region can be appreciated in the background satellite image.

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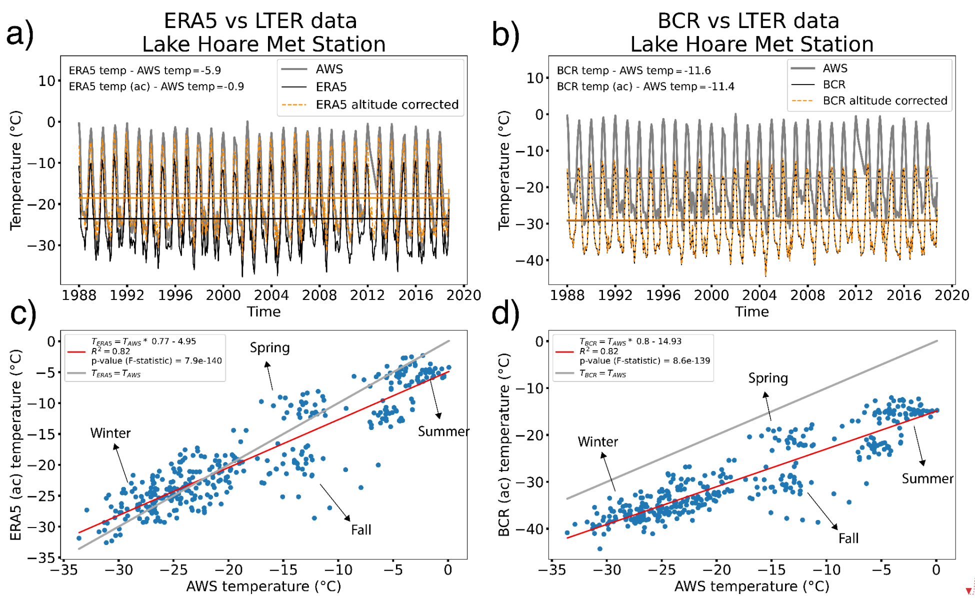
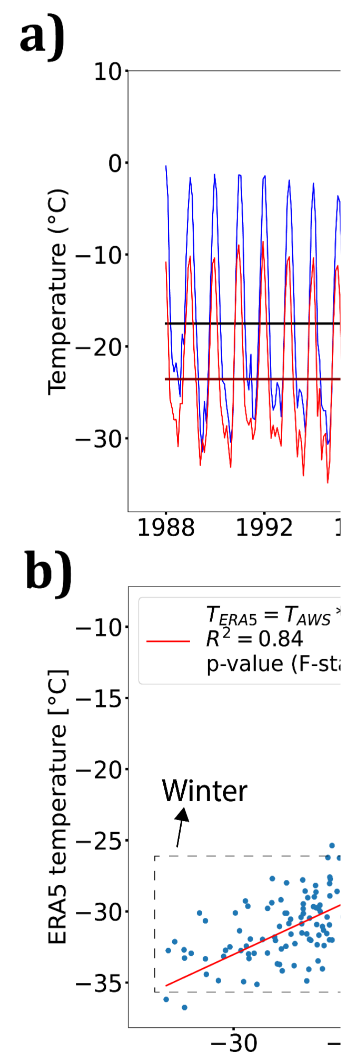


Figure. 2 Comparison of the monthly averaged 2-metre air temperatures recorded at station Lake Hoare (HOEM) and the values from the closest grid node of the ERA5 and BCR datasets. Time series of the AWS data (grey curve) compared to the reanalyses data (black curve) and the altitude-corrected (ac) reanalyses data (dashed orange curve) for the ERA5 (a) and BCR (b) datasets. The correlograms showing the best fit line to the relationship between the AWS temperatures and the ERA5 and BCR temperatures are shown in (c) and (d), respectively. Note the seasonal variation in the relationship, particularly the large bias during the summer months.



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AWS Location name	AWS ID	Latitude	Longitude	Elevation (m.a.s.l.)
Beacon Valley	BENM	-77.828	160.6569	1,176
Lake Bonney	BOYM	-77.7147	162.4646	64
Lake Brownworth	BRHM	-77.4344	162.7036	279
Canada Glacier	CAAM	-77.6133	162.9644	264
Commonwealth Glacier	COHM	-77.5646	163.2823	290
Explorer's Cove	EXEM	-77.5887	163.4175	25
Mt. Fleming	FLMM	-77.5327	160.2714	1,870
Lake Fryxell	FRLM	-77.6113	163.1701	19
Friis Hills	FRSM	-77.7474	161.5162	1,5910
Garwood Ice Cliff	GAFM	-78.0259	164.1315	51
Howard Glacier	HODM	-77.6712	163.0773	472
Lake Hoare	HOEM	-77.6254	162.9005	77
Miers Valley	MISM	-78.1011	163.7877	51
Taylor Glacier	TARM	-77.74	162.1314	334
Upper Howard	UHDM	-77.686	163.145	826
Lake Vanda	VAAM	-77.5257	161.6913	296
Lake Vida	VIAM	-77.3778	161.8007	351

Table 1. List of available AWS in the McMurdo Dry Valleys region.

AWS Location name	**AWS ID**	**Distance to closest ERA5 node (km)**	**AWS data date range**	**Average 2 m air temperature @ AWS**	**Average 2 m air temperature @ ERA5 node / altitude corrected**	**Average 2 m air temperature @ BCR node /altitude corrected**	**$ERA5_{mean\_temp}$ - AWS_{mean_temp} / ERA5 (ac)$_{mean\_temp}$ - AWS_{mean_temp}**	**BCR_{mean_temp} - AWS_{mean_temp} / BCR (ac)$_{mean\_temp}$ - AWS_{mean_temp}**
Beacon Valley	BENM	3.27	2000-12-11 - 2012-11-19	-21.4 ± 0.7	-33.5/-27.4 ± 0.7	-29.4/-35.3 ± 0.7	-12.1/-5.9 ± 1.4	-8.0/-13.9 ± 1.4
Lake Bonney	BOYM	1.84	1993-12-08 - 2018-10-09	-17.2 ± 0.6	-24.0/-16.9 ± 0.4	-29.3/-23.6 ± 0.5	-6.7/0.3 ± 1.0	-12.1/-6.3 ± 1.0
Lake Brownworth	BRHM	3.83	1995-01-23 - 2018-11-10	-19.9 ± 0.7	-25.4/-21.8 ± 0.5	-29.3/-30.5 ± 0.5	-5.5/-1.9 ± 1.2	-9.4/-10.5 ± 1.2
Canada Glacier	CAAM	1.71	1994-12-18 - 2011-01-05	-16.3 ± 0.7	-23.1/-20.3 ± 0.6	-29.3/-30.4 ± 0.6	-6.7/-3.9 ± 1.3	-13.0/-14.0 ± 1.3
Commonwealth Glacier	COHM	3.96	1993-12-06 - 2018-10-30	-17.6 ± 0.5	-22.1/-21.4 ± 0.5	-29.3/-20.6 ± 0.5	-4.4/-3.7 ± 1.0	-11.6/-2.9 ± 1.0
Explorer's Cove	EXEM	1.32	1997-12-05 - 2018-11-23	-18.9 ± 0.7	-21.7/-19.9 ± 0.5	-9.3/-18.8 ± 0.5	-2.7/-0.9 ± 1.2	-10.3/0.2 ± 1.2
Mt. Fleming	FLMM	3.7	2011-01-22 - 2018-11-11	-24.2 ± 0.6	-34.0/-27.1 ± 0.8	-29.2/-33.6 ± 0.8	-9.8/-2.9 ± 1.4	-5.0/-9.4 ± 1.4
Lake Fryxell	FRLM	1.45	1994-12-12 - 2018-11-19	-19.7 ± 0.7	-22.4/-19.3 ± 0.5	-29.3/-18.8 ± 0.5	-2.6/0.5 ± 1.2	-9.5/1.0 ± 1.2
Friis Hills	FRSM	5.28	2011-01-04 - 2018-11-06	-22.5 ± 0.6	-26.8/-28.0 ± 0.7	-29.2/-28.9 ± 0.8	-4.3/-5.4 ± 1.3	-6.6/-6.3 ± 1.4
Garwood Ice Cliff	GAFM	2.97	2012-01-24 - 2012-12-19	-16.6 ± 2.8	-23.6/-19.7 ± 2.3	-30.7/-29.9 ± 2.3	-7.0/-3.0 ± 5.1	-14.0/-13.3 ± 5.1
Howard Glacier	HODM	3.25	1993-12-04- 2018-10-31	-17.18 ± 0.4	-20.8/-20.5 ± 0.5	-29.3/-21.7 ± 0.5	-3.6/-3.3 ± 0.9	-12.1/-4.6 ± 0.9
Lake Hoare	HOEM	2.82	1987-11-25 - 2018-11-29	-17.61 ± 0.5	-23.5/-18.5 ± 0.4	-29.2/-29.0 ± 0.4	-5.9/-0.9 ± 0.9	-11.6/-11.4 ± 0.9
Miers Valley	MISM	0.31	2012-02-11 - 2018-11-06	-16.69 ± 1.00	-23.2/-19.9 ± 0.9	-29.5/-23.2 ± 0.9	-6.6/-3.2 ± 1.9	-12.8/-6.5 ± 1.9
Taylor Glacier	TARM	4.51	1994-12-05 - 2018-11-05	-16.9 ± 0.5	-25.4/-18.5 ± 0.4	-29.3/-25.3 ± 0.5	-8.5/-1.7 ± 0.9	-12.4/-8.4 ± 1.0
Upper Howard	UHDM	1.89	2001-11-28 - 2003-12-24	-16.56 ± 1.5	-20.3/-22.3 ± 1.7	-28.7/-23.5 ± 1.7	-3.7/-5.8 ± 3.2	-12.2/-6.9 ± 3.2
Lake Vanda	VAAM	2.87	1994-12-08 - 2018-12-07	-19.58 ± 0.7	-25.1/-20.0 ± 0.4	-29.2/-20.5 ± 0.5	-5.5/-0.4 ± 1.2	-9.6/-0.9 ± 1.1
Lake Vida	VIAM	2.47	1995-12-08 - 2018-11-14	-26.68 ± 1.0	-24.1/-20.8 ± 0.5	-29.3/-20.9 ± 0.5	2.6/5.9 ± 1.5	-2.6/5.8 ± 1.5

Table 2. List of comparison results between the temperatures recorded at the AWS and the closes ERA5 and BCR nodes. For each of the reanalyses datasets, we show the reported 2 m air temperature and the altitude-corrected (ac) value and their comparison to the average temperature at the AWS.

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